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CRYSTALLIZATION-DIFFERENTIATION IN IGNEOUS MAGMAS

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INTRODUCTION

A formal definition of the term magma is seldom given in petrologic literature, but it is plain from most writings that the word is intended to signify completely molten rock. Etymologically magma is perhaps more definitely applicable to a liquid with much suspended solid matter, that is, to a sort of mush. In this sense the term might designate igneous material in which crystallization was well advanced, and, while such usage should perhaps not now be urged, it is none the less true that magma in this latter sense is of fundamental significance in the genesis of igneous rock types. In his paper discussing the crystallization of magmas[1] in which that process was advocated as the fundamental factor in differentiation, the writer pointed out the special importance of two stages, the early stage of crystallization, when crystal settling may occur, and the late stage of crystallization, when squeezing out of residual liquid may occur. Throughout most of the discussion of crystallization-differentiation, however, particular attention was

[1] "The Later Stages of the Evolution of the Igneous Rocks," *Jour. Geol.*, XXIII (1915), Supplement.

given only to crystal settling. Since the publication of that paper a number of writers have pointed out various features of igneous rocks for which crystallization-differentiation has seemed to them to offer no adequate explanation. These objections have arisen largely from a failure to appreciate the importance to differentiation of the period when igneous material is largely crystalline, that is, the period when it is magma in that sense of the term to which attention is called above.

In the present paper the writer wishes to offer suggestions regarding some of the more general objections that have been raised against the theory of crystallization-differentiation and especially to apply it to certain phenomena for whose explanation it has been considered inadequate.

RELATIVE IMPORTANCE OF SYNTEXIS

In a recent paper on the "Genesis of the Alkaline Rocks" Daly discusses many features of the genesis of igneous rocks in general[1] and takes the opportunity of criticizing certain aspects of the theory of crystallization-differentiation. In his introduction and at other points in the discussion Daly makes statements that convey the impression that that theory, as a whole, must stand or fall with its ability to explain the alkaline rocks. A brief examination of the basis on which the theory rests will show, however, that such statements are hardly justified. From the results of a series of experiments that dealt with the crystallization of silicate melts the writer was led to the opinion that igneous rock types as we know them in the field could be developed as a result of the fractional crystallization of basic magma under appropriate conditions. The actual experimental work was carried on with mixtures of simpler constitution than the usual igneous rock, but frequently a fairly close approach to the composition of an igneous rock in its more essential aspects was accomplished. In such instances the conclusions drawn from the experimental work may be considered to be of correspondingly greater reliability. If we examine the experimental data we find that such close approach was made only in the case of the subalkaline rocks, and in the development of the

[1] *Jour. Geol.*, XXVI (1918), 97–134.

theory of petrogenesis it was only after these data had been applied to the problems of the subalkaline rocks that a possible solution of the alkaline rocks became apparent. In short, then, the conclusions arrived at in the case of the subalkaline rocks represent but a short extrapolation from the experimental data, whereas in the case of the alkaline rocks the extrapolation is a long one and correspondingly subject to error. While there is no reason at present for receding from the position taken regarding the genesis of alkaline types, it is quite possible that the position might prove wholly untenable without any necessary doubt being cast on the strength of the hypothesis that the subalkaline rocks, at least, are derived by processes of differentiation in which fractional crystallization is the primary control.

The writer's hypothesis, then, refers the diversity of igneous rocks to the differentiation of basic magma through a spontaneous power resident within the magma and resulting from its own crystallization. Daly's hypothesis likewise assumes original igneous material of a basic nature, but considers that it has little power of spontaneous differentiation and that it acquires a significant tendency to differentiate only when equilibrium is upset by the assimilation of foreign material. For each great family of igneous rocks a particular type of foreign material has been assumed to be the special agent. To Daly assimilation is all-important, to the writer it is a mere adventitious circumstance. There is nothing, however, in the writer's hypothesis that justifies Daly's statement that he assumes differentiation to affect only purely juvenile magma without foreign contamination.[1] Daly makes this statement in his discussion of the writer's definition of differentiation, in which discussion he directs his attention more toward the form than toward the substance. In another part of his paper (pp. 88 and 89) the writer describes his conception of the *differentiation of a magma that has suffered foreign contamination*. The interpretation that Daly puts upon the definition, while perhaps not an impossible one in the light of its wording, is rather surprising in anyone who has read the whole paper as carefully as Daly has evidently done. The phrase "without foreign contamination"

[1] *Jour. Geol.*, XXVI (1918), 117.

was inserted in the definition to make it expressive of the general agreement among petrologists to exclude from the category of differentiation those variations of igneous rocks that result purely and solely from assimilation of foreign material. That syntectic magma so formed could not suffer differentiation was no part of the intent of the definition.

In that part of the paper in which he discusses the differentiation of a syntectic magma the writer does, however, state his belief that such differentiation must usually be of limited scope, giving his reasons and describing the limiting factors. Contrasted with this is the assertion of Loewinson-Lessing, to which Daly offers adherence, that "a small degree of contamination with foreign material may change equilibrium in the magma, which, therefore, separates into strongly contrasted parts."[1] Such a generalized statement leaves one wondering as to the nature of the equilibrium referred to. Between what is the equilibrium? What is the nature of the strongly contrasted parts? Are they solid, liquid, or gaseous? Do rocks show the evidences of such processes? Have analogous processes been encountered in experimental science, and is the analogy of real significance?

In going on to a discussion of differentiation Daly proceeds to enumerate what may be called the units of differentiation. Some of these are presumably the strongly contrasted parts formed as a result of the disturbance of equilibrium mentioned above, but no particular mention is made of those that are to be so regarded, nor is any discussion offered of the manner in which solution of solid rock causes the separation of the units.

The units enumerated by Daly are the following:

1. Contrasted fluid phases of an initially heterogeneous magma, including parts particularly rich in volatile constituents.[2]
2. Solid crystals (fractional crystallization).
3. Mother-liquor left after partial crystallization.

[1] This is Daly's form of expression of the Loewinson-Lessing idea.

[2] Units of type 1 need not be considered, for according to Daly's own statements on the page immediately preceding, "rock phases resulting from originally different parts of the magma can be called differentiates only by destroying the useful definition of differentiation already adopted by most petrologists," and in this the writer concurs.

4. Non-consolute liquid fractions (liquid immiscibility).

5. Material of fused country rock, not diffused into the original magma (ultra-metamorphism in part).

6. Original magma locally charged with material dissolved from the country rock but slowly diffusing from the source of supply (syntexis).

Units 5 and 6 are plainly produced by the acquisition of foreign material but cannot be regarded as a separation of the original magma into contrasted parts as a result of this acquisition. The contrast is rather between the original magma and the included foreign material. No doubt such units are real factors in differentiation, but one may reasonably question whether they are of great importance. Differentiates formed from such material would have no necessary consanguinity with other differentiates formed from the magma itself, since their composition would depend principally on the nature of the included material, that is, on a purely accidental circumstance. It is, however, the fact that differentiates do normally show consanguinity that has led to the whole conception of differentiation in petrology. A differentiate formed by the accumulation of these clots of foreign material would necessarily show a very simple chemical relationship with the available foreign material. It is the fact that this simple relation does not exist that led Daly himself to reject purely marginal assimilation, and that should furnish an equally cogent reason for rejecting accumulation of xenolith material as an important factor.

Daly's case is much stronger in this respect when he assumes complete assimilation (usually abyssal) of the foreign material and subsequent differentiation of the syntectic magma, for then all the differentiates would show the requisite consanguinity. We are thus brought back to a consideration of the separation of phases (in the more definite physicochemical sense of the term) as the fundamental factor in differentiation, and the possible units then become those enumerated by Daly as 2, 3, and 4. The processes involved, namely the separation of a crystalline phase or of a non-consolute liquid phase, must be regarded as possible factors in the differentiation not merely of Daly's syntectic

magmas but of normal uncontaminated magmas. Daly considers differentiation as particularly prone to occur in syntectic magma because "equilibrium is upset" by the foreign material. The writer, on the other hand, gives his reasons for believing that the chilling effect normally consequent upon the immersion and solution of foreign material in a magma is sufficient to limit very materially the differentiation of magma that has been so affected,[1] and thus arrives at substantial agreement in this respect with Harker when he makes the statement, "Hybrid rocks are barren." In this connection it seems desirable to consider a statement made by Shand, to which Daly refers with approval.[2] The statement is that foyaitic or phonolitic magmas may enter "into chemical combination with the silica of invaded rock masses. *The reactions thereby induced would be exothermic and would tend to raise the temperature of the magma. The access of heat produced in this way would in turn enable the magma to perform a further amount of work in the way of mechanical solution.*"[3] In short, one might say that the addition of solid rock to a magma is, in this case and possibly in others, a mere adding of fuel to the flames. The conception probably had its origin in the long-used terms "acid" and "basic" as applied to igneous rocks, and in an unconscious extension of the analogy implied in these terms. It is true that when an acid is added to a base they unite with avidity, so much so that one must make the addition with care on account of the consequent rise in temperature. No such care is necessary when silica is added to molten nephelite.[4] Even at a temperature of 1550° C., where the product of the reaction (albite) is superheated over 400° C., silica dissolves in nephelite with excessive reluctance. Indeed experimental study suggests that the following general equation could be written with some confidence: molten rock + solid rock = molten rock $- x$ cal. It is not improbable, however, that, in some cases at least, the following equation would hold: molten rock + molten rock = molten rock $+ x$ cal. In other words,

[1] "The Later Stages of the Evolution of the Igneous Rocks," *Jour. Geol.*, XXIII (1915), Supplement, pp. 85–86.

[2] *Jour. Geol.*, XXVI (1918), 110. [3] Italics are mine.

[4] N. L. Bowen, "The Composition of Nephelite," *Amer. Jour. Sci.*, XXXIII (1912), 50.

it may be regarded as not improbable that two molten magmas might in some cases mix with evolution of heat, but that the solution of solid rock in molten magma is ever accompanied by evolution of heat may be regarded with extreme doubt. It is this reasoned conviction that has led the writer to limit the importance of assimilation.

LIQUID IMMISCIBILITY AS A FACTOR IN DIFFERENTIATION

Having in mind then the factors that may be considered to restrict the formation and differentiation of syntectic magmas, we may now return to the question of the separation of phases as the agency of differentiation of magmas, presumably dominantly juvenile and uncontaminated. The possible phases are, as we have seen, the units 2, 3, and 4 of Daly. Units 2 and 3 are, of course, necessarily concomitant, and to them the writer assigns the fundamental rôle in differentiation, but Daly is inclined to belittle their importance in favor of unit 4, that is, non-consolute liquid phases. The writer considers these to be non-existent in silicate magmas, this conclusion being based in part on experimental evidence. Not a single example of liquid immiscibility among silicates has been encountered in experimental work, in metallurgical practice, or in any of the many industries where molten silicates are treated. The single example of immiscibility of which there is good evidence in natural rocks, that between silicates and sulphides, is promptly revealed experimentally and in metallurgical practice. To many, however, the experimental evidence will never be convincing. When the range of experimentation with silicates shall have been extended to pressures of 20,000 atmospheres it will be possible to state that at pressures of 30,000 atmospheres wholly different phenomena might occur. Or again, an experiment made by human hands will probably never be prolonged to such a degree that its duration might be measured in centuries, so that it will always be possible to say that the time factor was not adequately considered. However, it is desirable to give some consideration to that experimental evidence which Daly brings forward, and which seems to him to indicate the probability of immiscibility under high

pressures. The suggestion is that high pressure may induce undercooling, and that immiscibility may result from the undercooling. This suggestion arose from experiments made by Bridgman, in which undercooling of liquids became more marked under higher pressures. Daly imagines that magmas may become similarly undercooled under pressure, and that in the undercooled condition unmixing may occur. Assuming the undercooling, it must be admitted that a certain possibility of the formation of non-consolute liquids is thereby introduced, for examples are known in which mixed liquids that are otherwise completely miscible develop immiscibility when undercooled. But such liquids reveal this peculiarity by having a freezing-point curve of a peculiar and characteristic shape.[1] Curves of this shape, or even remotely suggesting it, have not been noted among the liquidus curves for silicates, so that it may be regarded as unlikely that undercooling can develop immiscibility in silicates.

Quite apart, however, from the question of the probable effect of undercooling, we may point to the complete failure of igneous rocks to show evidence of undercooling when occurring in the largest masses available for human inspection, viz., batholiths. Indeed, if we consider the series that begins with a glassy lava, passes through a glassy lava with spherulites, through felsitic and fine granular textures, and ends with a coarse granular panidiomorphic texture, we find definite evidence of a continuous decrease in the degree of undercooling under which crystallization took place. The abyssal rocks are therefore characterized by a decidedly limited degree of undercooling, and the great magma reservoirs (if by this is meant something deeper than batholithic masses that become exposed) are exceedingly unlikely seats of significant undercooling. All of this is in accord with the laboratory experience that if one wishes to undercool a substance he must use a small quantity of it. The particular conditions not covered experimentally and urged by Daly as possible conditions favoring immiscibility do not, therefore, seem promising in that direction.

The writer's second reason for rejecting immiscibility is not adequately stated by Daly. He states it as being the "high

[1] Boeke, *Grundlagen der physikalisch-chemischen-Petrographie*, p. 113.

melting temperatures of olivine, magnetite, and other components of monomineralic rocks." This is in reality a collateral consideration, the reason being rather that natural rocks fail to show the kind of evidence that they would of necessity show were immiscibility a fact; indeed, it is incredible that anyone who has followed the process to its inevitable consequences could favor immiscibility in magmas.

A feature of igneous rocks that has led Grout,[1] Daly, and a number of others to favor immiscibility is the fact that two adjacent rocks that are evidently closely related frequently show a very abrupt transition from the one to the other. Yet a brief consideration of liquid immiscibility should show that it is not as likely to give discontinuous variation as is crystallization. It is true that if two liquids that are only partially miscible are shaken together in a flask two different liquids are formed, and if the flask be set aside they will become two separate layers with a definite bounding surface. If the temperature is kept constant these two distinct and sharply bounded layers will persist. However, if the immiscibility is the result of cooling a homogeneous solution the behavior is not so simple. In this case a certain amount of immiscible globules should form in the liquid when a certain temperature is reached, and, even if time were allowed then for the collection of the globules as a separate layer, more immiscible globules would form *in each layer* as soon as cooling was resumed. And when cooling had proceeded to the point where crystallization ensued a marked increase in the separation of immiscible globules would occur in association with, and as a necessary consequence of, the separation of crystals. We thus see that immiscibility is not a process taking place at an early stage of cooling as a result of which a sudden separation of a liquid into two liquid layers occurs. The separation is rather a formation of small globules that grow slowly by diffusion and can collect as a separate layer only by comparatively slow movement in response to gravity. Neither is immiscibility a process that is completed at a very early stage in the cooling history, and of which all evidence is destroyed. It is a process that may begin very early but must continue until the

[1] "A Type of Igneous Differentiation," *Jour. Geol.*, XXVI (1918), 656.

later stages of crystallization, and the evidence of it would be as obvious and unfailing as the evidence of crystallization itself. The complete collection of *all* the immiscible liquid as a separate and distinct layer is as unlikely as the complete collection of a kind of crystals whose separation continues until a late stage.

We may perhaps make clear these facts regarding immiscibility by discussing the simplest possible binary example. Figure 1 presents the temperature-composition relations. When a liquid of composition x is cooled to the temperature FK, liquid of composition K, that is, a liquid rich in B, begins to separate from it, and as cooling proceeds the composition of the one liquid changes along FE and of the other along KD. The liquid represented by points on FE decreases in amount, and that represented by points on KD increases in amount. The first separation of liquid must be represented by the formation of minute nuclei that grow to larger and larger globules as the cooling proceeds, and as a result of the slow diffusion of material to these globules. There is no reason why this process should be accomplished any more rapidly for separated liquid than for separated crystals. If the separated globules were heavier than the general mass of liquid they would sink, and here enters the possibility of the growth of these globules to much larger dimensions than crystals, because two globules encountering each other may coalesce. The formation of very large

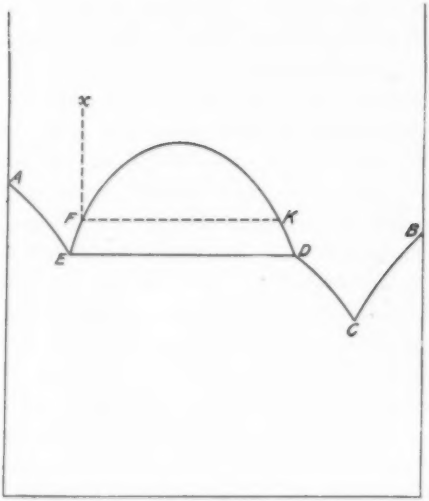

FIG. 1.—Illustrating behavior of a binary mixture with partial miscibility.

globules in this manner would result in their more rapid accumulation as a separate layer. It should be noted, however, that this rapidity of accumulation could never result in the complete accumulation of all the globules as a separate layer. If, for example, cooling were interrupted at some temperature between *FK* and *ED*, and time allowed for the accumulation of all the globules as a separate layer, as soon as cooling was resumed new globules would form in each layer, and their accumulation by the slow process of gravitative adjustment would begin again. It is plain then that whatever complications are assumed the magma must arrive at the temperature *ED* in a blotchy condition, many of the blotches being of rather large dimensions as a result of the coalescence of globules. By large dimensions is meant a diameter several times, perhaps very many times, the diameter of the crystals in the average plutonic rock. At the temperature *ED*, when the liquids in equilibrium have the composition *E* and *D*, crystallization begins, crystals of *A* separating. It is important to note the nature of the first crystals separating, for it will be recalled that the liquid separating was rich in *B*. Those who advocate the separation of olivine, pyroxene, plagioclase, etc., as immiscible liquid tacitly assume a correspondence between the kind of material that would separate early as a liquid and the kind of material that we know from experimental and petrographic experience separates early as crystals. As a matter of fact there is no necessary relation, and the fact that correspondence must be assumed in each individual case is sufficient in itself to throw doubt on a process requiring such an assumption.

Continuing the consideration of the cooling of the mixture, which had been carried to the stage of the beginning of crystallization, at the temperature *ED*, we find that crystals of *A* would separate, and that as a necessary consequence more liquid of composition *D* would be formed and some liquid of composition *E* would be used up. These reactions would continue at constant temperature with the amount of crystals *A* and the amount of liquid *D* increasing at the expense of liquid *E* until finally all of liquid *E* would disappear, when the whole mass would be made up of about 80 per cent of crystals *A* and 20 per cent of liquid *D*. We thus see that up to a time when the mass is largely crystalline two liquids are

present, and the crystalline product cannot fail to show the blotchy condition that this predicates. The evidence of immiscibility would not be confined to rapidly chilled flow and dike rocks alone, though it would presumably be especially clear in them. Further cooling would result simply in the separation of more crystals of *A* with a consequent change in the composition of the liquid from *D* to *C*, where eutectic crystallization of both *A* and *B* would occur. It will be noted too that the liquid *C*, which is the *last* material to crystallize, is closely related in composition to the liquids *K-D*, the *first* material to separate as a liquid. This is important in connection with the well-recognized parallelism between "Differentiationsfolge" and "Kristallizationsfolge." If liquid immiscibility were a prominent factor, or even a subsidiary factor, in the differentiation of igneous rocks no such parallelism would exist.

If we return now to those discontinuous changes of composition in associated igneous rocks that have led to the suggestion of immiscibility, we may make the discussion more concrete by referring to a specific case for which immiscibility has been invoked, viz., the case of the Duluth laccolith. Grout has concluded that the material of this great laccolith or lopolith, as it has been called, was intruded as a homogeneous magma, that crystallization-differentiation controlled by convection currents and gravity ensued, whereby the peridotite and banded gabbro were produced, and that when a certain stage of crystallization had been reached the material of the red rock separated from the gabbro as an immiscible liquid.[1] The first stages of this process, with modifications that are perhaps not fundamental, the writer is able to agree with, but he can see nothing in the described Duluth rocks to warrant the assumption of immiscibility, nor indeed in any other igneous series that shows this association of gabbro and granophyre without intermediate types. The kind of immiscibility assumed by Grout, namely that which ensues only after a certain amount of crystallization has occured, is in no sense different from that which we have discussed. Indeed some of the liquids of the system described show this behavior, viz., those having a composition lying between *A* and *E* (Fig. 1). This liquid, which formed only after crystallization

[1] *Jour. Geol.*, XXVI (1918), 658.

was well advanced, would form throughout the gabbro, and some of it would have to rise through several thousand feet. Granting that this was possible at a certain stage and complete accumulation of the liquid took place, what has become then of the further quantity of like liquid that must have separated when the conditions causing its first separation became intensified, that is, when crystallization of the gabbro was carried farther? Unquestionably clots of such material should occur everywhere throughout the gabbro. When it is realized too that experimental studies have shown beyond peradventure that a material rich in alkalic feldspar and free silica is a possible crystallization residuum of a gabbro magma and especially of an olivine gabbro the assumption of immiscibility is seen to be quite gratuitous. This is more especially true for that great number of examples where the acid material occurs in part as granophyric interstices in the gabbro phase, for there it is plainly a crystallization residuum occupying crystallization interstices and not occurring as the clots that one would expect of an immiscible liquid.

CRYSTALLIZATION AS THE CAUSE OF DISCONTINUOUS VARIATION

This association of gabbro and granophyre without intermediate types, of which Grout has collected a number of examples from the literature, is a feature of igneous rocks well recognized by the writer.[1] It is true that in discussing crystallization-differentiation it was shown that a complete series might be formed, extending from gabbro to granite with every intermediate step, but there is no necessity that the series be complete. Only in a very large mass is such a series to be expected, where not only the great size but conditions of comparative quiet concurred to produce great freedom in the settling of crystals. In masses of moderate size the differentiation, if it can be so called, may be a localized affair occurring about each individual crystal, where the separation of the earliest crystalline material from its mother-liquor is accomplished not by its sinking but by the formation of zones about it. In this case the late differentiate occurs merely as interstitial material. If this zoning action is combined with only a limited amount of sinking of

[1] N. L. Bowen, "The Problem of the Anorthosites," *Jour. Geol.*, XXV (1917), 227.

crystals one can obtain a mass showing the last liquid as an upper layer and also as interstitial material in part of the rest of the mass. This is likely to give a pair of rocks showing that marked contrast between a granophyre on the one hand and a diabase or gabbro with only granophyric interstices on the other. Daly has failed to grasp the significance of zoning in producing granophyric interstices and seeks to destroy the whole theory of crystallization-differentiation at one fell blow by pointing out that pyroxene, olivine, and plagioclase have not sunk out of granophyric diabase.[1] It is not necessary that they should, for the prevention of reaction between crystals and the liquid from which they separated may be accomplished, as we have seen, not only by a spatial separation but also by a localized mechanical separation due to zoning.

There is, however, a third method of separation of liquid from crystals that is probably the principal agent of production of those discontinuous variations frequently seen in rock series and particularly that shown in the gabbro-granite (granophyre, etc.) association. It is the squeezing out of residual liquor at a stage when the mass is largely crystalline, and it is many times more promising as a possible cause of discontinuous variations than is any process of limited liquid miscibility, which, as we have seen, is a continuous process requiring the slow action of gravity as an ally and not significantly more competent than crystal settling to produce discontinuity. This squeezing out of liquid is a process that is at first thought difficult to visualize, yet it is one that must be a very real factor in igneous rock genesis. It is the sort of thing one may see at any time when walking on the wet sand of a beach. The foot leaves a slight imprint in the sand that is surrounded by an area where the surface of the sand is particularly wet. The mass as a whole is sensibly incapable of flow, so that the pressure of the foot results merely in a more efficient close-packing of the sand grains coming immediately under its influence, with a consequent squeezing of water into the surrounding sand, where some of it exudes upon the surface. On the other hand, in very wet sand or in mud the whole mass may flow under the foot. The filter-press action

[1] *Jour. Geol.*, XXVI (1918), 121.

exhibited by the sand is but roughly analogous to the phenomena possible in a partly crystallized magma but may serve as a starting-point in the discussion. The relative movement of liquid with respect to crystals by this general method is probably not normally possible with rock materials before the crystals have grown together into a mesh. In order to discuss the action here suggested we shall assume specific cases and consider, as well as may be, the mechanics of the process.

Laccolith with upper late differentiate.—Assume that a sheetlike mass of magma is injected between two members of a sedimentary series, with slight arching of the upper member so that a flat laccolithic mass is produced. The fact that the sheet was injected at that horizon may be regarded as being probably determined by the competency of the member immediately above it. If this terrane is being acted upon by a compressive thrust the tendency will be to shorten the lateral dimensions, and the competent member will yield by forming a more pronounced arch, while the relatively incompetent beds immediately beneath the mass will yield by shortening and thickening. This action, going on slowly, will result in a thickening and shortening of the laccolithic mass, which offers no resistance until crystallization has proceeded to such an extent that the crystals touch each other and have grown together into a strong framework. When sufficiently strong this crystal mesh may finally be able to sustain the thrust and cause a pause in the shortening action. The condition then existing might be represented by Fig. 2*a*. The stress may accumulate until finally the crystal mesh begins to break down, whereupon the beds beneath will yield as before, and the competent beds above will bend as before. Likewise, coincident with the beginning of the breakdown of the crystal mesh the interstitial liquid will feel the pressure of the thrust and will transmit it hydrostatically to all parts of the mass, and the vertical

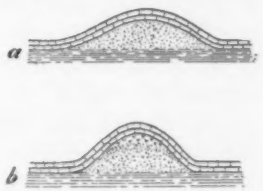

FIG. 2.—(*a*) Laccolith at an advanced stage of crystallization; (*b*) same after being subjected to lateral pressure at this stage. Shows squeezing of residual liquid (late differentiate) into the crown of the arch.

component of this hydrostatic pressure on the liquid will aid in emphasizing the up-arching of the beds of the roof. As the crystal mesh *progressively* breaks down, and the horizontal dimensions are shortened in consequence of closer packing of crystals, there will be a flow of the interstitial liquid into the space developed by the up-arching of the roof. All three actions—shortening of the lateral dimensions by closer packing of crystals, up-arching of the roof, and movement of the liquid—go on *pari passu* and are thoroughly interdependent. When the crystals have become sufficiently closely packed to withstand the thrust the whole action must cease, and of course may cease sooner for other reasons. The resultant mass is therefore, in the simplified case we have assumed, a laccolith showing marked differentiation, with a rock represented by crystalline material separated from the original magma as a lower differentiate, and as an upper differentiate material represented by a late residual liquid (Fig. 2*b*). The differentiation would be markedly discontinuous, the later differentiate would have an intrusive relation to the earlier in places, in other places there would be a rather abrupt transition, and yet the relations would not indicate successive intrusion in the ordinary sense of the term. In so far as this action is incapable of occurring before a certain degree of crystallinity has been attained, there should be a tendency toward a fairly constant contrast between the two differentiates in the matter of composition. On the other hand there is no necessity for constant relative proportions in their amounts. Associated igneous rocks when formed by this method should present, therefore, a fairly constant hiatus as compared with the complete igneous series that is capable of production under other circumstances. Any mass, not necessarily of the simple shape we have assumed but capable of being acted upon in the same general manner, should give a closely related result, so that the general phenomenon might well be of widespread occurrence. The gabbro-granophyre association fulfils every requirement.

An example of the extreme simplicity we have pictured will of course never be found. One of the principal complications results from the fact that the freezing of such a mass will take place from the outer layers inward, except for such modification of this behavior

as is introduced by crystal settling. As a result of this more advanced consolidation of outer layers an upper layer may become more or less definitely a part of the upper competent member of the stratified series and may act in conjunction with it during the process of up-arching. The later differentiate would not normally, therefore, be the uppermost. It would, indeed, be located more nearly toward the central part of the mass according to the degree of this freezing inward from the roof.

Sheet with thin central late differentiate.—In certain cases where the freezing has been nearly symmetrical at the top and bottom of a sheetlike mass a horizontal thrust, occurring at a time when there was still a thin layer mostly liquid centrally placed, might cause a general shortening of the lateral dimensions of the sheet, with consequent thickening vertically. These would take place concomitantly and would be accomplished by closer packing of the crystals in the outer layers, where crystallization was well advanced, and a thickening of the originally thin central liquid layer by inflow of the interstitial liquid from the outer layers. There would thus be formed a mass having a thin central later differentiate with an intrusive to transitional relation to its surroundings, and with a distinct tendency toward a streaky development, for the liquid squeezed in from the layers where crystallization was well advanced would differ from the liquid already present in the narrow central band when this action began.

Thick central late differentiate.—There is also a very simple method whereby a sheetlike mass, whether dyke or sill, can develop locally a very thick, centrally placed layer of this late differentiate. It is the warping of the containing walls of the sheet, with consequent thickening of the sheet in a certain place and thinning of it elsewhere. If this takes place at any time except at a late stage of crystallization it will normally have no significant result in the way of differentiation. If it takes place at a time when the crystal mesh has considerable strength it may have important consequences. We shall consider a segment of the sheet including a part that has been thickened. Figure 3*a* represents part of the original sheet and Fig. 3*b* the same after warping of the walls. In the section where the sheet is thinned the crystal mesh will be broken down and

the crystals more closely packed. There is an intermediate neutral zone in which the sheet retains its original width and the crystal mesh remains undisturbed. This portion therefore acts as a permeable partition through which the interstitial liquid of the thinned portion passes.[1] As the walls begin to move apart in the thickened portion the crystal mesh will part along a median plane, for there it is weakest, and the interstitial liquid from the thinned portion will flow in to occupy the space afforded. At no time will there be any space in the sense of empty space. The movement of liquid into the space will be absolutely concurrent with, and perhaps a contributing cause of, the development of the space. The action will continue until a proper balance of the forces involved is reached. In certain sections the thickness of the sheet may be increased to several times its original value, and the late differentiate may be a very thick central band, indeed several times as thick as the narrow bands of the early differentiate on either wall. The thinned portions will normally be thinned only a moderate amount, so that relatively large areas must be thinned. The late differentiate would again have an intrusive relation to the earlier material on the walls, with, however, "welded" contacts and locally a transitional relation of a more or less abrupt nature. This action could take place only at a late stage of crystallization, when the crystal mesh had very considerable strength, if only for the reason that the neutral zone must have sufficient strength to withstand a considerable difference of hydrostatic pressure on opposite sides of it, for there would be very great frictional resistance to the flow of liquid.

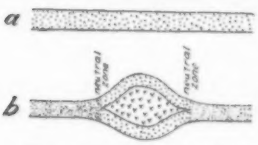

FIG. 3.—Sections of a tabular mass, dyke, or sill: (*a*) at an advanced stage of crystallization; (*b*) after warping of walls at this stage and squeezing of residual liquid (late differentiate) into expanded section.

[1] For the purpose of presentation of the conception in particularly simple form this definite neutral zone is assumed. Its existence is, however, not essential to the action described. It is merely necessary that the breakdown of the crystal mesh should go on progressively as stated on p. 408. This will bring it about that the portion not yet broken down acts at any instant as a permeable partition preventing the passage of crystals and permitting the passage of liquid from the portion breaking down at that instant.

It is suggested that the various kinds of filter-press action that have been discussed hitherto probably cannot take place before the mass is 80 per cent crystalline. In all cases we should have a marked hiatus in the crystallization series that could have formed under conditions favoring continuous differentiation, that is, conditions favoring crystal settling. Even with the slow cooling and the quiet cooling requisite for crystal settling a certain amount of the filter-press action we have discussed may occur when crystal accumulation has proceeded to the appropriate degree.[1] No general discussion of the combined effect will be attempted. Instead an explanation will be offered for the phenomena exhibited by the special example, the Duluth lopolith.

DIFFERENTIATION IN THE DULUTH LOPOLITH

On this igneous mass Grout has recently published an interesting series of papers. It is a large, sheetlike body mainly of gabbroid composition but showing differentiation, with masses of peridotite at the bottom, a great thickness of olivine gabbro with striking banded effects and anorthositic facies, and at or near the top a so-called "red rock" or granophyre. Grout thinks that crystallization was a prominent factor in the production of differentiation, and that convection was the dominant agent in bringing about the observed distribution of crystals. There was also a wholly different type of differentiation, according to Grout, which involved the separation of the red-rock magma from the partly crystallized gabbro magma as an immiscible liquid. To this latter phase of his conclusions certain objections have already been offered that later will be referred to again. Any type of differentiation in which crystallization is the fundamental factor is, in the writer's opinion, much more likely to occur, and any promising process that may be put forward as conducive to the localized accumulation of crystals is unlikely to meet with opposition from the writer. Convection does not, however, seem to offer any promise. Grout introduces a type of convection called two-phase convection, in which a mass of liquid containing suspended crystals is considered

[1] A combination of the two actions is probably the most promising explanation of many monomineralic masses.

to act as a unit and to sink in virtue of its greater aggregate density. It was evidently suggested by Daly's two-phase convection, in which the two phases involved were liquid and gas that gave a low aggregate density. It is known that masses of foam possess some of the attributes of a rigid body, and it might therefore be expected that localized highly vesicular masses of lava might act as a gravitative unit, but nothing is known to warrant the extension of the idea to a liquid containing suspended crystals. Moreover there appears to be no necessity for appealing to this unlikely process, since ordinary thermal convection would be equally effective and can hardly fail of occurrence in a cooling mass of magma.[1] However this may be, we may now proceed to consider the supposed effects of convection. Grout makes some calculations on the rate of convection which indicate that crystals formed at the cooling portion near the top could be carried to the bottom in half an hour. No reason is offered for this precipitate haste. Undoubtedly many years were available; indeed Daly considers the time available to be embarrassingly long and offers it as an objection to crystal settling that the results are often very meager when the duration of crystallization is considered. Moreover, it should be realized that a current that could carry crystals down in half an hour could carry them up again in half an hour, particularly a current in which a mass of liquid with suspended crystals is supposed to act as a unit. The lagging behind and lodgment of the crystals at the bottom as the currents sweep over the floor, which Grout considers would occur, would undoubtedly be a factor in the case of ordinary thermal convection at any rate (its possibility in the two-phase convection pictured by Grout may be doubted). It should be realized, however, that this occurs in spite of convection and in virtue of the superior density of the crystals rather than in virtue of convection, and the really important question is whether crystals would accumulate at the bottom more effectively by this dragging-behind process than they would by simple settling. In other words, does convection act as an aid or as a deterrent to

[1] It should be noted that the writer has never doubted the reality of convection in magmas. He merely doubts its efficacy in producing differentiation.

crystal settling? The answer suggested by experience is that it would act as a deterrent. Sedimentation in nature is always delayed by convection, and in the laboratory when one wishes to make separations by means of heavy solutions one always obtains a more ready separation by jacketing the heavy solution in order to prevent even the very moderate convection that results from the slight draughts in the laboratory.

Perhaps, however, the more important reason for advancing convection was not its greater efficiency in bringing about accumulation of crystals as compared with the "far-fetched" process of settling of crystals. Possibly the particular reason was the banding of the gabbro. In order to explain the banding it is necessary, however, to assume a simplicity of convection that experience of that phenomenon does not warrant. It is known, for example, that a mass of liquid experiencing convection may divide up into columnar cells of hexagonal section, each of which has its own system of convection characterized principally by vertical currents. While it need not be urged that convection in a large mass of magma would be exactly of this nature, it seems inevitable that a very large number of currents would be set up whose motion would be principally vertical, and that any banding of the rock that might result from convection would be principally vertical. There seems little reason to believe in a great current sweeping over the floor and depositing its load in bands parallel to the floor in the manner Pirsson[1] and Grout have suggested. However, assuming that such a current did exist, it is noteworthy that in order to explain banding it is necessary to make the further assumption of a rhythm in crystallization, such that the crystals brought down by convection vary in their nature as time goes on and may even alternate. And convection is supposed to have a remarkable advantage over crystal settling in producing alternation of layers as a result of this rhythmic crystallization. But while I do not urge rhythmic crystallization I would point out that the crystals brought to the bottom by settling would show precisely the same alternation as those brought there by convection if this rhythmic crystallization can be assumed.

[1] *The Igneous Rocks of Highwood Mountains*, U.S. Geol. Survey, Bulletin 237.

When we come to a consideration of the more intimate details of crystallization we find this same tendency to urge an advantage of convection over settling, an advantage that has no real existence. In the case of the bodies of magnetite, for example, it is pointed out that the best concentrations are centrally placed in the gabbro and not at the bottom, and to explain this it is pointed out that magnetite is, "at least partly, later in time of crystallization" and "would remain liquid until the lower parts of the chamber were filled with rock." Is the explanation not equally applicable to the process of crystal settling? Is there anything in that process that demands the settling of a crystal before it exists? It is true that the writer referred to the accumulations of iron ore as evidence of settling of crystals because they have been described by others as occurring at the base of the Duluth mass, and it is safe to say that in many cases some of the iron ore crystallizes very early, but the writer has always been opposed to the unrestricted acceptance of the notion that all the ore minerals separate early.[1]

We come now to that very special feature of the near-uniformity in the nature of the plagioclase in all parts of the gabbroid portion of the mass, a feature that has been considered to favor especially the idea of convection. Vigorous convection would of course keep plagioclase crystals suspended and in a slowly cooled mass would permit perfect adjustment of their composition to that of the surrounding liquid, so that there would be no necessity of the appearance in the final product of any very basic plagioclase, bytownite, or anorthite. But the rôle assigned to convection by Grout is not so much that of keeping crystals suspended as that of aiding in their accumulation in layers by dragging along the bottom, and, at a time when the rhythm of crystallization was in a phase such that the crystallization of plagioclase dominated, the layer formed is supposed to show a corresponding dominance of plagioclase. These plagioclases, dragging behind and caught in the viscous border, have according to Grout "there slowly, maintaining equilibrium, adjusted their composition to that of the surrounding magma." It should be realized, however, that in so far as basic

[1] N. L. Bowen, "The Order of Crystallization in Igneous Rocks," *Jour. Geol.*, XX (1912), 457.

plagioclases accumulate at a certain place in excess of the amount that could have separated from the liquid at that place, the liquid there surrounding them is incapable of completely making them over into the average plagioclase of the mass.[1] It makes no difference how the excess of plagioclase arrived at that place, the laws of physical chemistry will not be suspended in favor of those arriving by the convection route. The fact that those portions of the mass that are particularly rich in plagioclase do not have significantly more basic plagioclase than other parts may therefore be regarded as a very serious objection to accumulation of plagioclase by convection and indeed to any process involving the accumulation of plagioclase by a positive active motion on its part relative to the liquid from which it separates.

The theory of crystal settling, however, does not demand any positive action of plagioclase, at any rate not until a quite late stage of crystallization. Just as settling is not regarded as possible for a crystal that does not yet exist, so it is not regarded as possible for a crystal unless it is heavier than the liquid. Grout is able to refer to a place (p. 33) where I have discussed the effect of the sinking of plagioclase, but reference to that page will show that there simple mixtures of albite and anorthite are being discussed. Manifestly basic plagioclase crystals will sink in a liquid having the composition of more acid plagioclase, but if femic material is dissolved in the liquid the problem is not so simple, and on another page of the same paper (p. 79)[2] reference is made to this fact. There the following statement is made: "It appears, indeed, that plagioclase crystals may at the earlier stages of crystallization be only very slightly heavier than the liquid at most and possibly even somewhat lighter." In another paper this suggestion is elaborated and the behavior of plagioclase is discussed at some length.[3] It is pointed out that plagioclase "remains practically suspended in the liquid with probably a very slight tendency to rise at first and the whole of the liquid is available for the production of the change of composition that ensues as the temperature falls. Thus, though

[1] N. L. Bowen, "The Problem of the Anorthosites," *Jour. Geol.*, XXV (1917), 212.

[2] These page numbers refer to those in "The Later Stages of the Evolution of the Igneous Rocks," *Jour. Geol.*, XXIII (1915), Supplement.

[3] N. L. Bowen, "The Problem of the Anorthosites," *Jour. Geol.*, XXV (1917), 211.

the earlier crystals of plagioclase are basic bytownite, they are, in nearly all cases, gradually made over into labradorite by the liquid in which they remain suspended." The statements could hardly be more specific, and Grout's reference (with its accompanying objections) to my statement regarding a simple mixture of anorthite and albite is hardly to the point when such definite consideration of the actual case of gabbroid magma has been offered. We have seen then that the specific objections to crystal settling that Grout offers are in part due to a misconception of that process, and that in many cases where he supposes a convective action to have advantages over settling the advantage has no real existence as far as explanation of the phenomena of the Duluth gabbro is concerned. However, it must be conceded that Grout's main contention is substantially correct, viz., that the theory of crystal settling in the simple and generalized form in which it has been stated does not offer an adequate explanation. We have seen that his convective action is likewise inadequate. As an offset to so much destructive criticism a constructive suggestion will be ventured. The suggested explanation will involve two principal assumptions: first, that the igneous mass of the Duluth lopolith was injected as a sensibly homogeneous and completely liquid magma, and secondly, that the action which produced the basin-like form of the mass took place in part contemporaneously with the period of crystallization of the magma. The first of these conclusions is, it should be remarked, in complete accord with Grout's conclusions. Under five heads Grout points out the impossibility of belief in the intrusion of heterogeneous liquid, a process that the writer has suggested as a possible result of the squeezing of liquid from a crystallizing mass.[1] This suggestion should be applied only to cases where the evidence is strong that there were two liquids. I am wholly in accord with Grout that it is a quite inadequate explanation of the banding of the Duluth mass and indeed of most rocks showing primary banding. Usually such banding is to be referred to movement during crystallization.[2]

[1] N. L. Bowen, "The Later Stages of the Evolution of the Igneous Rocks," *Jour. Geol.*, XXIII (1915), Supplement, pp. 27 and 83.

[2] N. L. Bowen, "The Problem of the Anorthosites," *Jour. Geol.*, XXV (1917), 236 and 237.

We shall begin then with a mass of gabbroid magma wholly liquid and already injected into its present position. When cooling had reached a certain stage crystallization began, and the earliest crystals, olivine and perhaps some titaniferous magnetite, were precipitated. As a result of currents in the liquid, whether from thermal convection or wholly mechanical causes, free settling of crystals was much hampered, so that a large proportion of the crystals remained suspended. In spite of this deterrent action, however, some of the crystals of these early minerals did accumulate on the bottom, where they formed masses of peridotite and presumably also of iron ores in some cases. In the meantime, crystallization of both pyroxene and plagioclase had begun. The plagioclase was at first a basic bytownite. It remained suspended because nearly of the same density as the liquid, and, as cooling and crystallization proceeded, it adjusted its composition to approach labradorite. The free sinking of pyroxene was hampered, presumably by currents, as was that of olivine, so that no accumulation of pyroxenite was accomplished. A certain amount of accumulation of pyroxene did occur, however, together with that of olivine, and the pyroxene crystals augmented the mass of peridotite at the base. There was also a certain part of the liquid from which both olivine and pyroxene crystals had settled out practically completely and that contained only suspended plagioclase crystals.

The mass is now entering a stage when in its lower portions, constituting say one-fifth of the total thickness, crystals are in contact with their neighbors and are beginning to grow together at corners and along edges. This action becomes important when the residual liquid and the crystals have each about one-half the volume of the total mass. In the upper portions the crystals are somewhat more widely spaced, the more so as the height above the base increases, but this feature is not so very marked, because crystal settling has been limited by the lack of quiet conditions. The bottom-most layers including peridotite may be regarded as practically entirely crystalline, with only a small proportion of residual liquid.

Origin of banding.—There is then a tendency toward a layering of the mass on a very large scale but no suggestion whatever of

the complicated banding that the finally solidified rocks show. In order to explain the production of banding it is necessary to assume that the action that produced the basin-like shape of the mass was going on continually during the period of crystallization. When the proportion of crystals was small this action could have no effect on the distribution of materials, but when the proportion of crystals began to pass the 50 per cent mark it may have had an important effect.

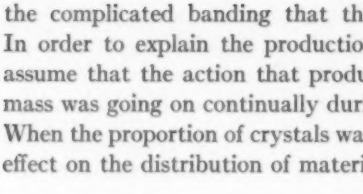

FIG. 4.—Showing the effect of warping on a crystallizing mass: (*a*) shows portion of a mass when it reaches stage at which warping begins to be effective; (*b*) shows the effect of warping causing compaction of crystals locally and the formation of lenticular pools of residual liquid. Density of stippling is intended to indicate the relative, though not absolute, degree of compaction of crystals in various parts immediately after the action. Final result is a banded rock showing that contrast in composition that existed between liquid and crystals at the time of the action.

We shall consider, for simplicity and convenience, the possible results of the bending action as applied to segments of two adjacent layers. The bending will tend to produce a shortening of the upper layer relative to the lower one, and a shortening thrust is therefore developed in the upper layer. This upper layer may reasonably be supposed to have certain portions that are relatively weak and others relatively strong that may be illustrated diagrammatically as in Fig. 4. It may be supposed too that all of the yielding to this shortening thrust will take place in the weak portions of the layers, and that the strong portions will act as practically rigid plungers. The yielding of the weak portions will likewise relieve the strong portions from any bending force, and a strong portion can therefore retain its original shape, with the consequent development of a long, narrow space between it and that part of the lower layer immediately adjacent to it. At first thought it would seem impossible that this space could develop, and if by space is meant empty space this impression would be entirely justified, for the strong segment, though capable of acting as a rigid plunger, would have no real strength as an arch. It should be noted, however,

that the strong segment and indeed the whole crystal mesh which we are considering is a thoroughly porous material permitting free passage of the liquid residual magma under its hydrostatic head. A space between the two layers could therefore develop freely, for it would fill with liquid as fast as it opened. The yielding of the weak segment, the opening of a long, narrow space between the bridgelike strong segment and the lower layer, and the filling of this space with the residual liquid would therefore go on simultaneously and indeed would be thoroughly interdependent. The yielding of the weak segment would be the result of the breaking of the relatively weak crystal mesh at the points where crystals had begun to grow together, and once instituted it would continue until the crystals were packed together rather closely with only a little residual liquid, or until the mass had acquired a strength equal to that of the segment that was acting upon it as a plunger. At this time the action would cease as far as the yielding of that particular weak segment was concerned. As a result then of this single episode two layers have been produced whose direction is practically parallel to the base of the igneous mass, one of them having a composition practically equivalent to that of the residual liquid contained in the crystal mesh at the time, and the other a composition not far from that of the crystals that had separated at the time (Fig. 4*b*). If we consider the further history of this particular part of the igneous mass as cooling and further bending proceed it will be found that the segment that had yielded will, when a certain amount of growing together of the already compacted crystals takes place, constitute a particularly strong segment and in virtue of its strength may be the means of production of a layer of the same type as itself, from a relatively weak segment sensibly along its strike, by acting as a plunger and compacting that segment. At the same time the plunger segment will produce immediately beneath itself a band of the opposite type. It is thus seen that the action, once begun, is a means of its own growth and is particularly competent to produce adjacent strongly contrasted bands. Constant repetition of this action as cooling and warping proceed should produce innumerable bands such as those seen in the Duluth mass.

If we return to a consideration of the fundamental action involved, namely the formation of a bridge as a result of the refusal of a certain layer to bend in conformance with the bending of the layer immediately beneath it, we find that this could take place only when the crystal mesh is of such a nature as to have fair compressive strength but very little tensile strength. If the tensile strength were even moderate the upper layer would be pulled into conformable shape by the lower layer, for the tension acts over a relatively large area. The crystals of the mesh must therefore be in contact but must be grown together only to a very limited degree. There is a further reason why the proportion of crystals to liquid must be limited. The bridging action can take place only when the crystal mesh is so open that pressure on the liquid is transmitted to all parts of it with great freedom and with little frictional resistance, for the bridge has no real strength to support a significant superincumbent load, and liquid must be free to flow into the space immediately below it if the potential bridge is to become a reality. On the basis of some rough experiments it is estimated that the action could take place when the mass was 50 per cent crystalline but probably not when the proportion of crystals was significantly less than that value. On the other hand, it probably could not take place when the proportion of crystals was as great as 65 per cent. The contrast between bands is therefore of a different order of magnitude from that shown in the gabbro-granophyre association. There is likewise a rather limited period for any particular portion of a mass during which this action can occur. It is believed that during this period and as a result of the action described the banding of the Duluth gabbro was produced. In this case it is possible to show the relation between the direction of banding and the forces that produced it. For many igneous masses having primary banding this relation would perhaps not be so plain, yet it would seem to be safe to state it as a general proposition that primary banding is produced by the action of warping stresses, torsional stresses, and in some cases shearing stresses, acting at the appropriate stage of crystallization.

Origin of the red rock.—Returning now to the Duluth lopolith, we find it at a stage when crystallization is fairly well advanced.

As a result of continued warping banded structure has developed in successively higher and higher horizons, broadly speaking, though as the top was approached the conditions would vary considerably, and it would seem likely that banding would not be produced as readily. However this may be, we may consider that the stage of possible development of banding has passed, and that the whole mass is approaching complete crystallinity. The lower portions pass through this stage somewhat sooner that the higher portions and finally become completely crystalline, the liquid adjusting itself continually to the composition of the crystals with which it is in contact, until finally all the liquid is used up. In upper portions some interstitial liquid still remains, and principally in those parts from which olivine has been removed by gravity the interstitial liquid becomes of a granitic nature. As the plagioclase crystals, continually adjusting their composition, approach labradorite, Ab_1An_2, the plagioclase content of the liquid approaches acid andesine, and the actual proportion of the interstitial liquid becomes rather small. This is the stage at which a lateral thrust acting on the mass may produce a squeezing upward of residual liquid and a packing together of the crystals after the manner discussed in some detail on an earlier page. It may be noted that in the upper portion of the mass the warping becomes more nearly a simple compressive thrust resulting from the tendency toward the folding in of the two horns of the crescent so that the squeezing out may be regarded simply as a result of a continuance of the warping action and as expressing its result at quite a late stage of crystallization. There is even a very definite suggestion in the shape of the lopolith as mapped of a departure from the simple crescentic form. This departure is, as might be expected, localized where the red rock is developed in force and is of the nature of a bulging of the roof (Fig. 5). Add to this the fact that the plagioclase of the red rock is on the average precisely the proper plagioclase for a liquid in equilibrium with the general plagioclase crystals of the gabbro, and it becomes rather obvious that one is, to say the least, hasty who dismisses crystallization-differentiation as a possible explanation of the gabbro, red-rock association. The red rock has, on the contrary, all the earmarks of a crystallization residuum that could have been

squeezed upward by lateral compression of part of the gabbro mass. Grout, in offering objections to crystallization-differentiation as an explanation of the red rock and in discussing in that connection the composition of the liquid, states that "before it reaches the composition of such a granophyre as the red rock of Duluth a large amount of feldspar must have crystallized from a magma too acid to yield basic labradorite."[1] On another page, however, he describes the red rock as amounting to "less than 300 feet of acid andesine." Now the liquid that is in equilibrium with Ab_1An_2 crystals is precisely of the composition of acid andesine, to be more-

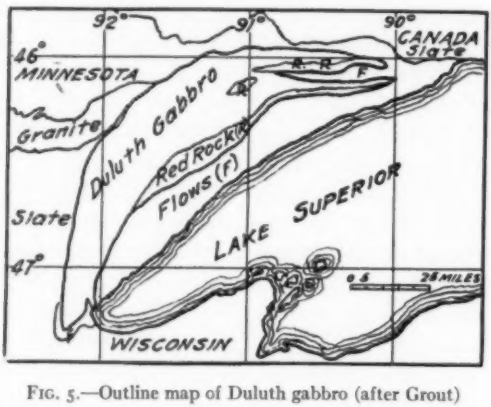

FIG. 5.—Outline map of Duluth gabbro (after Grout)

specific Ab_3An_1, so that Grout's objections fall when examined in the light of his own detailed descriptions. If the red rock represented an immiscible liquid it is rather remarkable that at the time at which it had separated it should have a composition appropriate for this final plagioclase composition.

In connection with this particular association, namely that of granophyre and gabbro, a rather definite suggestion as to conditions of possible immiscibility has been offered. It has been suggested that on account of immiscibility between water and silicates the magma separates into two liquids, the one water-rich and the other

[1] "A Type of Igneous Differentiation," *Jour. Geol.*, XXVI (1918), 645.

silicate-rich.[1] Apart from the objections that have been raised against immiscibility in general, principally with reference to the lack of evidence of the intermediate steps of the process, a further objection should be pointed out that is applicable to this particular type. The contrast between the two liquids should be of this nature, that the one liquid should be mainly a silicate melt with a little water in dilute solution, and that the other liquid should be mainly water with a little silicate in dilute solution. Now, while it is well recognized that the granophyre of the association to which we have reference is characterized by having a greater amount of water than the gabbro, no one would go the length of claiming that the granophyre magma was mainly water with a little silicate in solution. While having, on first thought, some degree of probability the action contemplated does not appear to represent the actual phenomenon.

THE ORIGIN OF NODULES, SCHLIERS, AND RELATED PHENOMENA

Immiscibility has been invoked as an explanation of other phenomena of igneous rocks, principally the formation of monomineralic nodules and of large rock masses of a monomineralic nature. For immiscibility of this nature not even the first-thought probability can be conceded. Substances freely miscible above a certain temperature do not become absolutely immiscible on cooling, with consequent separation of pure end components as liquids. The liquids separating would of necessity be polycomponent solutions, possibly quite strongly contrasted, but nevertheless polycomponent. The liquids must likewise be solutions capable of separate existence at the temperature concerned, and in emphasis of this temperature aspect of the problem it has elsewhere been pointed out that pure molten olivine, for example, can hardly be credited at temperatures near the crystallizing range of olivine basalt. It has been suggested that the liquid need not be pure olivine but could be olivine with volatile components in solution.[2] The obtaining of such a liquid is, however, sensibly the same problem as the obtaining of molten olivine. Any liquid that separated

[1] Evans, "Congrès Geologique International," *Compte-Rendu* (XXIIe Session, Canada, 1913), p. 248.

[2] Daly, *Jour. Geol.*, XXVI (1918), 123.

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should be polycomponent with respect to its silicate content alone. A volatile component enters the system merely as a component that would distribute itself between the two separating liquids in accordance with a definite partition coefficient which is the ratio of its solubility in the two liquids. Even if we strain a point and assume that one of the liquids could be monomineralic it is necessary to imagine that volatile components distribute themselves between the two liquids in such a way that the monomineralic liquid gets many times as much as the polycomponent liquid in order that the former may remain molten at the temperature concerned. In other words, it is necessary to assume that volatile components are many times more soluble in liquid olivine, say, than in liquid basalt. Apart from the unlikelihood of such a relation the real weakness of the whole case becomes apparent when, in order to explain monomineralic masses of pyroxene, it becomes necessary to assume that volatile components are many times more soluble in liquid pyroxene than in liquid basalt, and in order to explain an anorthositic facies it is necessary to assume correspondingly greater solubility of volatile material in molten plagioclase than in molten basalt. Finally, if it is insisted that this chain of successively dependent phenomena, each fundamentally unlikely, to say the least, may nevertheless represent the facts of the case we may still turn to monomineralic rocks themselves and see if they give evidence of *excessive richness* in volatile components or so-called mineralizers. It was with this reasoning in mind that the anorthosites were examined and found to give no evidence of the presence of mineralizers *in excessive amounts*.[1] Scrutiny of the other monomineralic rocks will, it is believed, yield a like result. The marked serpentinization of peridotites is probably sometimes effected by waters of atmospheric origin (not by weathering), and where accomplished by magmatic solutions there is little reason for believing that these solutions belonged to a peridotite liquid rather than to adjacent igneous masses frequently congeneric with the peridotite.[2]

[1] N. L. Bowen, "The Problem of the Anorthosites," *Jour. Geol.*, XXV (1917), 231.

[2] Benson, *Amer. Jour. Sci.*, XLVI (1918), 710.

It has been considered that the nodules consisting mainly of a single mineral and occurring fairly frequently in basaltic rocks may represent immiscible liquid globules. Olivine nodules in basalt are perhaps the commonest examples. The term nodules is rather misleading, for they are characteristically angular and justify the conclusion of a great number of petrographers that they are fragments torn from a mass of olivine rock (Olivinfelseinschlüsse). Rosenbusch, however, always insisted that they represent intratelluric crystallization from the rock mass in which they are found. As a matter of fact it is more reasonable to suppose that both conceptions are true, and that the nodules represent fragments torn from an olivine rock that was formed from the basalt by crystallization-differentiation. It is not necessary to suppose that the olivine settled to the bottom of an intratelluric mass of basaltic magma; indeed the characteristic occurrence of the nodules in narrow dikes and small necks of basalt suggests an action that may be of considerable importance in petrogenesis. The suggested action is the formation of crystal jams, or the clogging of the channels occupied by moving magma as a result of the packing together of crystals at a constricted point, in much the same manner as log jams and ice jams are formed in rivers. Any marked constriction of a channel in which a liquid is flowing that contains suspended solids, even in very small amount, is likely to cause such clogging. The formation of a crystal jam is highly probable in a narrow dike or neck through which basaltic magma is flowing with upward of 10 per cent olivine crystals suspended. Once formed the clogging may result in the accumulation of a considerable mass of crystals, and the passing of liquid through the mass, a liquid from which olivine and only olivine is being precipitated as yet, may cause the growth of the crystals of olivine until no interstices are left. Accumulation of pressure on the magma, aided perhaps by terrestrial disturbance, may then break the barrier and carry the olivine rock along as inclusions of the nature of olivine nodules, some of which may become rounded as a result of the resorption that olivine normally suffers. While the clogging of a channel with very early crystals, such as olivine, is to be expected only in small channels, there is reason to believe that even large channels might be similarly affected

at later stages of crystallization, and in this case, while the disrupted mass would not give monomineralic inclusions, it might readily give inclusions strongly contrasted with the magma that would produce schliers and related irregularities in the rocks formed.

In the banded peridotites of Skye, Harker describes seams of nearly pure picotite and chromite. It is possible that these may have been formed by some such action as that described above. However this may be, the petrologist should look askance at molten spinel and chromite. Molten corundum, molten olivine, and molten magnetite even with volatile components in solution are to be similarly regarded, and every possibility of explaining masses of such minerals as the result of crystal accumulation from complex magmas or of hydrothermal action should be exhausted before the probability of such melts is entertained, for the chemical difficulties in the way of their production are colossal. By hydrothermal action is meant introduction by dilute solutions as contrasted with introduction as a melt, even though it be a melt with volatile material dissolved.

ORIGIN OF THE ALKALINE ROCKS

Throughout the foregoing pages consideration has been given to phenomena exhibited only by the so-called subalkaline rocks. For such rocks we can speak with considerable assurance regarding the chemical effects of relative movement of crystals and liquid, because systems approaching them reasonably closely in composition have been completely investigated. Concerning the alkaline rocks we cannot speak with the same assurance, for not much more than a beginning has been made in their experimental investigation. Nevertheless some consideration will be given to the alkaline rocks, particularly to the question of the relationship between alkaline and subalkaline magmas. The writer has stated elsewhere the opinion that the most important of the alkaline magmas, foyaitic magma, is definitely related to granitic magma. The equilibrium reactions which take place in granitic magma, and of which the evidence is plain from the occurrence side by side of feldspars, mica, and quartz, furnish a clue to the origin of foyaitic magma. The principal reactions indicated are the breakdown of

polysilicate molecules into orthosilicate molecules and free silica, and they may be written empirically as follows:

$$KAlSi_3O_8 \rightleftharpoons KAlSiO_4 + 2SiO_2,$$
$$NaAlSi_3O_8 \rightleftharpoons NaAlSiO_4 + 2SiO_2.$$

Certain other reactions no doubt occur, such as

$$H_2O + NaAlSiO_4 \rightleftharpoons HAlSiO_4 + NaOH,$$
$$H_2O + KAlSiO_4 \rightleftharpoons HAlSiO_4 + KOH,$$

which are simple examples of hydrolysis. That such reactions are going forward in the liquid is attested by the fact that certain of the products are precipitated, the polysilicate molecules as feldspar, the orthosilicate molecules $KAlSiO_4$ and $HAlSiO_4$ in mica, and free silica as quartz. Evidently certain other products not precipitated are stored up in the liquid, and the principal of these is $NaAlSiO_4$, the liquid becoming highly alkaline and showing a high concentration of water and other volatile components when finally precipitation has taken place to such an extent that the liquid is a very small proportion of the total mass. The compound $NaAlSiO_4$, the distinctive molecule of foyaitic magma, can be precipitated from this liquid only if it is removed from the presence of quartz. In the presence of quartz the reaction is simply reversed, and the polysilicate feldspar is precipitated instead of the orthosilicate nephelite. It is not impossible that rapakivi structure and certain perthites whose albite lamellae appear to have been formed by reaction may represent the stage of reversal of this reaction. It is not essential that such structures be present, however, for commonly the using up of this liquid would be accomplished merely by continued growth of albite or closely related plagioclase crystals. There does appear, however, to be a particular tendency toward a precipitation of albite later than that of orthoclase (rapakivi-like though not necessarily having the particular rapakivi structure) in granites that are related to nephelite syenites. It should be noted, however, that this highly alkaline and highly aqueous liquid that is thus formed as the crystallization of granite becomes far advanced is a very fugitive material, and that the crystallization of a large mass of granite must proceed very slowly at this stage.

Throughout a long period this liquid is therefore more or less free to escape into the surrounding rocks, where it is used up in producing metasomatic reactions of various kinds. The materials of this liquid may therefore be frequently, perhaps normally, unrepresented in the igneous sequence for this very reason. Foye has brought forward quantitative evidence of the introduction of alkaline material in great quantity from granitic magma. Following Daly he imagines that these alkaline liquids have been produced by reaction between limestone and granite, but it is not at all clear how this can be considered to apply to the particular case under discussion. In its original form the limestone-syntectic hypothesis was rather simple, and, as the writer has stated elsewhere, it assumed rather likely reactions. The most important reaction was the taking of silica by the lime to form lime silicates, the free silica being used up first and later some of the silica of feldspar molecules with consequent production of feldspathoids. However, it is imagined in this particular case that limestone reacts with granitic magma but does not desilicate it, in fact leaves it still a granitic magma, and yet reacts in such a way as to produce large amounts of alkaline liquors, of which part are introduced into the invaded limestones and part crystallize with formation of nephelite syenite. The manner in which this can occur is by no means so easily followed. On the other hand, it appears to afford a natural explanation if it is supposed that biotite granite magma is normally capable of supplying this alkaline liquid, and that it is produced by reactions of which we have direct evidence in the granite itself. The liquid may be used up by introduction into surrounding rocks or by partial reversal of these reactions if it remains in the interstices of the granite. On the other hand, if it is separated from the granite in such a way as to form a distinct liquid it will give rise to a mass of nephelite syenite and may indeed further differentiate to give derivatives of nephelite syenite.

In the paper in which this mode of origin of nephelite syenite was proposed it was stated that a continuance of the process of settling of crystals could produce nephelite syenite from granite in the same manner as granite itself may be produced from gabbro. This manner of separation of the liquid from the crystals is not now considered likely, indeed the essential reactions have probably

not proceeded adequately until a late stage in the crystallization of granite, when crystal settling was no longer possible. The only method of separating the liquid at this stage is the method of the squeezing out of residual liquid by the breaking down of the crystal mesh under the action of outside forces. If this be true, alkaline magma can be produced only as a result of the action of outside forces, whereas subalkaline magmas, while they too can be so generated, may nevertheless be generated spontaneously by crystal settling. It is possible then that the alkaline rocks might show a tendency toward a definite relation to earth movements[1] not exhibited in the same degree by subalkaline rocks, but the writer is unable to see at present what the details of this connection may be.

The succession of igneous rocks deduced from the foregoing considerations—from basic through silicic to alkaline—has been discussed in some detail elsewhere.[2] An objection to this has been raised on the basis of the fact that in the Pacific basin there are basic rocks and alkaline rocks and none of the intermediate silicic rocks.[3] It should be noted, however, that these objections are based entirely on the evidence of effusive rocks and the occurrence of a magma, as an effusive mass depends on certain factors other than its generation within the crust of the earth. Daly has, for example, presented figures that show that granitic material is twenty times more abundant than basaltic as deep-seated masses, whereas basaltic material is fifty times more abundant than granitic as effusive masses. There is therefore something about granitic magma that limits very seriously its occurrence in effusive types, even though it may be abundantly present as subjacent masses. We need not go into the question of what these factors may be, though some readily suggest themselves. The significance of the fact in this connection is that the types that happen to be exposed in an effusive sequence may give but a poor indication of the genesis of their magmas, and it may be taken as a general rule that fundamental relationships are much more likely to be deducible from plutonic masses. When we turn to the evidence of plutonic masses

[1] Such as that suggested by Harker in the classification into Atlantic and Pacific types.

[2] "The Later Stages of the Evolution of the Igneous Rocks," *Jour. Geol.*, XXIII (1915), Supplement, pp. 55 ff.

[3] Holmes, *Science Progress*, XI (1916–17), 68.

on this question we find that they speak in no uncertain voice regarding the intimate connection of silicic with alkalic rocks.

This association of silicic and alkalic rocks, we have seen reason to believe, is of fundamental significance and is a fact very difficult of explanation on the basis of the limestone-syntectic, desilication hypothesis. Ordinary granites, nordmarkites, and highly siliceous alkaline granites are world-wide associates of nephelite syenites.

In yet another respect the limestone-syntectic hypothesis lacks support. The proponents of syntexis as a general phenomenon frequently support their claims by pointing to the fact that fragments of siliceous rocks immersed in gabbro frequently show rims of a granitic nature about them, and that fragments of quartzite immersed in nephelite syenite may show rims of alkaline granite. These and like observations at least demonstrate the possibility of certain reactions, though one may still doubt their quantitative importance in petrogenesis. In the case of the reaction between feldspar-bearing magma and limestone to produce feldspathoid-bearing magma no support of this kind is to be found. Magmas of all subalkaline types have at times included blocks of limestone that have been made over into lime-silicate rocks, yet in no case are these inclusions surrounded by rims of alkaline rock. The limestone-syntectic hypothesis lacks, therefore, even that measure of support that is afforded syntexis in other cases through the occurrence of the reaction aureoles mentioned.

SUMMARY

In this paper some of the objections that have been raised against the theory of crystallization-differentiation are considered, and its adequacy to explain certain phenomena, for which it has been considered to fail, is pointed out. The supposed advantages of liquid immiscibility in explaining discontinuous variations are considered, and reasons are given for believing that no such advantages exist. On the basis of crystallization explanations are suggested for discontinuous variations, particularly those noted in the association gabbro-granophyre. A suggestion is made as to the origin of primary banding with particular reference to the Duluth lopolith.

THE RICHARDTON METEORITE

T. T. QUIRKE
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At 9:48 P.M. Mountain time, June 30, 1918,[1] a meteorite was seen to fall in the country between Richardton and Mott, North Dakota. Pieces fell on both sides of the line between Stark and Hettinger counties within a strip about 9 miles wide from north to south and 5 miles wide from east to west. The center of this area lies in altitude 46°37′30″ N. and longitude 102°16′17″ W., about 20 miles south of Richardton.

The following data in regard to finders and specimens have been collected. The finds are arranged in geographical order from north to south.

Names of Finders	Section	Township	Range	Specimens	Weight	
					Pounds	Ounces
Rochus Steiner	26	137	92	1 piece in fragments	6	12
Geo. B. Steiner	?	137	92	1 piece	13	.....
Nickolas Kuntz	27	137	92	1 piece	11	8
				1 piece	2	10
Bernard Kuntz	27	137	92	1 piece said to weigh	9	.....
				1 piece	2	4
Lewis Loran	33	137	92	1 piece	18	5¼
				1 piece	7	0½
				1 piece	4	.....
				1 piece	0	12
Frank Miller	12	136	93	4 fragments	7	.....
Leo Kern	18	136	92	11 pieces (largest 3 lbs.)	9	5½
Mat Schmidt	18	136	92	15 pieces	7	.....
Benedict Fried	24	136	93	24 pieces (½ to 2½ lbs.)	17	.....
Jacob Fried	26	136	93	4 pieces	1	.....
Jozim Olheiser	28	136	92	3 pieces	2	13

This lists a total of 71 pieces, weighing 123 lbs. 6 oz. It is reported, however, that at least 60 lbs. of material in addition

[1] The date was erroneously reported as July 26, 1918, in a preliminary statement in *Science*, New Series, Vol. XLIX (Jan. 24, 1919), p. 92.

to some of that listed above were purchased on the spot by Mr. T. A. Treganza.[1] It is probable that about 200 lbs. of material have been recovered from the fall, of which the Loran boloid, weighing 18 lbs. 5½ oz., appears to be considerably the largest.

As noted in the description of Modoc,[2] the distribution of the members of a meteorite fall follows in general the order of their size, with the largest pieces farthest in the direction of flight. The Richardton meteorite fell toward the north, and all the units weighing more than three pounds apiece came from the most northerly strip, 2 miles wide, while only one small specimen, weighing 12 oz., was found there. On the other hand, although the number of pieces found in the southern end is greater than that found in the northern part of the area, nearly all the individual examples are small.

The Richardton meteorite is of the veined, spherical chondrite class (Cca) of Brezina's classification, as may be recognized from the following descriptions of those specimens which have been studied by the writer. The descriptions are arranged in order of the size of the specimens.

1. The Loran specimen, weighing 18 lbs. 5½ oz. (8,338 gm.), may be likened in shape to an axe-head. It is a five-sided wedge, the sharp edge being 20 cm. long, and the blunt end 12 cm. by 11.2 cm. From back to edge the piece is 18 cm. long. Part of the crust has been broken from the mass, especially from the corners. In fact the corners of most large specimens are battered because the meteorite fell at a low angle to the surface of the earth, so that most of the pieces seem to have rolled or bounded after striking the ground. Few pieces penetrated the soil and none is known to have broken through the sod.

The largest Loran specimen appears to have six subparallel veins, the traces of three of which can be followed entirely around the mass, but the other three split up into branches and are less definite. All the veins branch into two or more members, and in

[1] The writer has sent three letters to Mr. Treganza, Britt, Iowa, in regard to his purchases. However, as none of these letters brought a reply, no further information about this interesting collection can be offered in this article.

[2] O. C. Farrington, *Nat. Acad. Sci.*, Mem. XIII (1915), p. 307.

some places the branches reunite, in the manner of anastomosis. Here and there within them there is a concentration of troilite and iron. The traces of the veins stand out like welts upon the unbroken surfaces (Fig. 1); otherwise the surface of the meteorite seems fairly smooth, although variegated with the characteristic shallow depressions, like thumb-prints, which are common to many stony meteorites. In addition to the subparallel veins before noted, there are at least two others roughly at right angles to them, which are less clearly marked than the series of six. It may be there are really more than two in this group. In any case, they are not prominent, and either they are discontinuous, or else the vein-filling material is wanting in places, making them inconspicuous on that account.

The crust seems to be of equal thickness on each face, apparently being a secondary fusion surface everywhere except on the side shown in Fig. 1, which appears also to have been the side protected from the rush of air after disruption of the meteorite. All the surfaces show the system of tiny cracks, like the crazing of china, which is common to stony meteorites.

On places from which the crust is broken it can be seen that the matrix of the stone is pale gray, speckled with pale brown chondrules as large as 3 mm. in diameter. The matrix is friable and easily broken, the chondrules breaking freely out of the matrix. There appears to be a good deal of troilite, but the iron does not show so clearly because it lacks the reflecting fracture faces which make the troilite apparent.

2. The Loran specimen weighing 7 lbs. ½ oz. (3,186 gm.) is an irregular hexahedron with three pairs of subparallel sides. It may be described as an irregular rhombohedron, of which two axes are at right angles to one another, the third axis being at approximately right angles to one axis and inclined at an angle of about 80° to the other.

The crust is almost complete except for one side, which is a nearly plane fracture surface. Almost parallel to the fractured face are veins which can be traced completely around the stone. The fracture face itself follows one of the veins, so that much of the surface is vein material. This vein is cut by two short

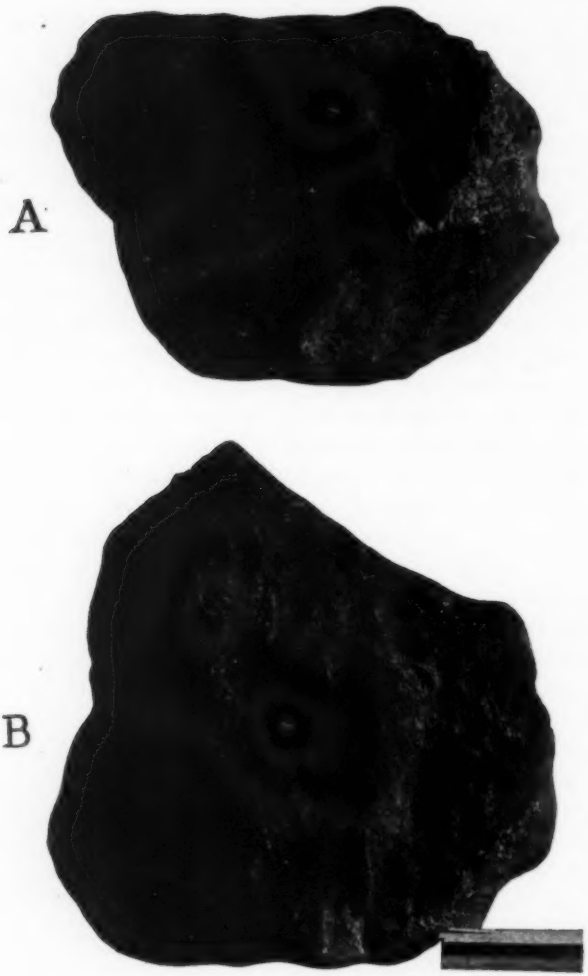


FIG. 1

A, The large, wedge-shaped specimen of the Richardton Meteorite, lying on one side, the edge of the wedge being to the left, showing traces of the veins on the smooth, primary-fusion surface.

B, Side view of the same specimen standing on the smooth face shown above, showing the secondary-fusion surfaces developed after disruption of the meteorite. The two lower corners are broken. The scale reads in centimeters.

cross-veins and offset by one. The veins in this specimen seem to be composed largely of troilite. Troilite is disseminated throughout the stone and forms ledges along the veins.

3. The largest member of Kern's collection is a well-crusted specimen, bounded by one flat side and a hemispheroid. The flat surface appears to be a fracture plane following a troilite vein. The stone weighs 1,357 gm.

4. A seven-sided boloid found by Nickolas Kuntz, weighing 2 lbs. 10 oz. (1,192 gm.), is covered with shallow depressions of the common finger-print type. It shows several veins of more than one group. There is no smooth face which may be interpreted as that sheltered during flight.

5. Preserved at the University of North Dakota is a very black coated specimen found by Bernard Kuntz, weighing 1,022 gm. One side is smooth, showing clearly the traces of intersecting veins, and the other faces are pitted with shallow depressions. Either the smooth face was the side away from the rush of air during flight, or it is of earlier origin than the rough faces, which may be secondary surfaces fused over after disruption during passage through the atmosphere.

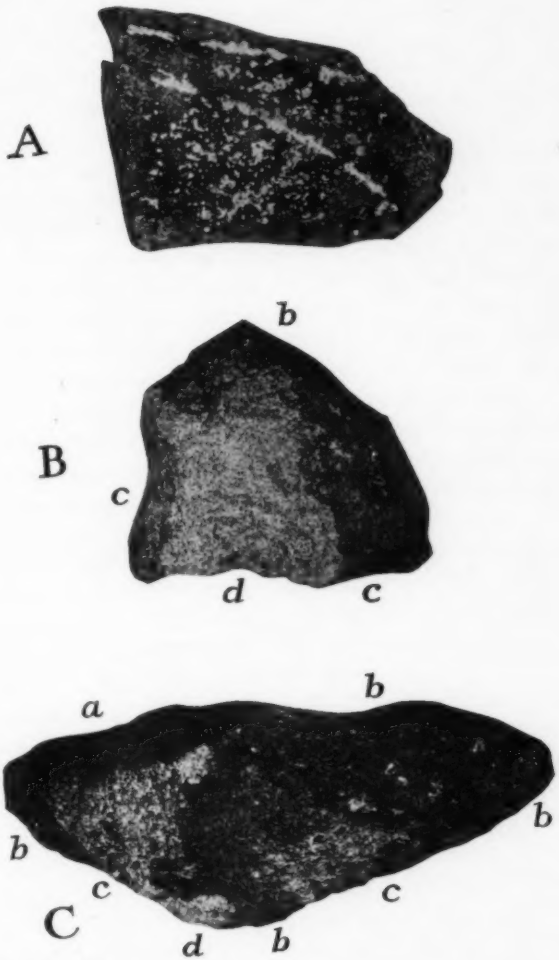
6. Fourteen small pieces weigh 515, 498, 349, 312, 309, 305, 240, 232, 207, 168, 163, 161, 127, and 123 gm. respectively. These specimens are rounded boloids covered with fused crust, angular fragments completely covered with fused crust of various degrees of denseness, pieces broken either by impact with the ground or during examination by the finders, and combinations of these groups. In many cases troilite in melted blebs embosses the fused surfaces, indicating that many secondary faces follow the planes of veins.

This group of small specimens furnishes evidence of at least three degrees of fusion. First, there are black faces which are very smooth and show the traces of veins as welts, apparently sides protected from the direct impact of air in flight. Other black faces are dappled with small finger-print-like depressions, lumps and depressions being equally covered with fusion crust, having been corroded apparently by the blast of hot air compressed in front of the meteorite during its passage through the

air. Second, there are rough surfaces, not smoothed by fusion and still bearing the roughness of original fracture, burned to a dark-brown color, the points being rounded off and black, but the depressions being unfused in places. These areas cut sharply across the black, well-fused faces, and are clearly of later origin. Third, a few small fragments have some surfaces only slightly fused; perhaps the words "scorched" or "singed" well describe the degree of fusion. Only the points of rough, broken surfaces are blackened by fusion, most of the area is light gray and unfused, but here and there outstanding pyroxene chondrules and troilite grains have melted and run a few millimeters over the unfused material. These faces, in some cases, are in the form of spalls out of the other types of fusion crust. It is clear that they are the youngest of the fused surfaces (Fig. 2, *B* and *C*).

Under the microscope it can be seen that these stones are composed chiefly of olivine, monoclinic pyroxene, glass, metallic iron, and troilite. The texture is markedly chondritic. The matrix consists chiefly of small crystals and fragments of olivine and pyroxene scattered throughout a scanty, glassy matrix. The chondrules are of the following types: (*a*) Spheroids, each composed of part of an olivine crystal. (*b*) Spheroids, each composed of part of a pyroxene crystal. (*c*) Little spheroids of colorless glass. (*d*) Larger spheroids containing well-defined olivine crystals. In some examples the crystals are crowded together, in others they are scattered in the glassy ground-mass of the chondrule. In a variety of this type the crystals appear to be arranged with their crystal axes parallel. (*e*) Glassy chondrules with radiating and fibrous cryptocrystalline texture. Some of the large pieces of olivine show many minute inclusions in irregular linear distribution.

A notable characteristic of this meteorite is the veining (Fig. 2, *A*). The veins are composed chiefly of troilite, and metallic iron and nickel. They are not continuous, for they contain areas in which there is no metallic material. The veins seem to vary in different cases from containing almost nothing but metal to carrying only troilite. In most cases metal and sulphide are mingled in a manner which suggests contemporaneous deposition or con-



Photograph by W. A. Force

FIG. 2

A, A polished surface showing the apparent concentration of metal in veins. Some of the chondrules have so high a polish that one must look closely to distinguish the metal from the polished chondrules.

B, A specimen showing the natural fracture face (*d*), the tertiary fusion surface (*c*), and a little of the secondary fusion surface (*b*).

C, A specimen showing all degrees of fusion: (*a*) indicates the primary, (*b*) indicates the secondary, (*c*) indicates the tertiary fusion faces, and (*d*) indicates the broken, unfused interior of the meteorite.

centration. Parts of the veins have been examined in both polished surfaces and in thin sections under the microscope. The metal seems to have been deposited without any violence having affected the chondrules, as a general thing; however, one chondrule seems to be represented by only half a sphere, the metal being in juxtaposition with the plane side. In most cases, nevertheless, the metal or sulphide partly surrounds or incloses the unbroken chondrules. The writer has seen no case of a chondrule penetrated by metal, although some of the chondrules include tiny grains of troilite in bordering zones. In cases where both metal and sulphide are in the vein the two are mingled in irregular shapes which have a smooth surface of contact; in some cases the troilite is scattered both within and near the borders and outside the metal, in other cases taking the place of the chief constituent of the vein and containing small irregular grains of metal.

Iron and troilite veins are not uncommon in stony meteorites. In some cases both minerals are present, and in others there is but one. Of American falls the following are reported definitely to contain iron veins: Danville,[1] Marion,[2] Farmington,[3] Estacado,[4] and Pipe Creek.[5] Troilite veins are reported in both McKinney[6] and Cosby Creek.[7] In most of these the iron and sulphide are concentrated apparently in the veins, although in most other meteorites the iron and troilite are disseminated in irregular grains throughout the mass. The relations of the minerals are commonly obscure; for example, Bath Furnace[8] has troilite intruding riven metallic particles as though of younger age than the iron, and also troilite completely enclosed in iron, indicating the opposite. But in Allegan[9] the sulphide does not occur as blebs within the iron as the silicates do, indicating that it is not necessarily either antecedent or contemporaneous with the iron. In the case

[1] Farrington, *op. cit.*, quoting Smith, p. 156.

[2] *Ibid.*, quoting Brezina, p. 296.

[3] *Ibid.*, quoting Meunier and Preston, p. 187.

[4] *Ibid.*, quoting Howard and Davison, p. 174.

[5] *Ibid.*, quoting Brezina, p. 353.

[6] *Ibid.*, quoting Brezina, p. 291.

[7] *Ibid.*, quoting Shepard, p. 138.

[8] *Ibid.*, quoting Merrill, p. 50.

[9] *Ibid.*, p. 30.

of Richardton, however, the troilite and iron seem clearly to be contemporaneous.

Polished surfaces, parallel to a vein and cutting the vein, totaling a surface of 10 sq. cm., show nickel iron containing irregular grains of troilite, in which there are three specks of metallic copper, the largest grain measuring about 0.6 by 0.08 mm. This seems to be the first report of metallic copper in a meteorite. Copper has been determined in traces by chemical analysis, but the character of its occurrence was unknown. It has been remarked before that, whatever the conditions under which metallic iron and nickel are deposited in these and similar veins in meteorites, the conditions must have been reducing in the extreme. It is not surprising, therefore, that, with iron in the reduced forms of ferrous sulphide and metal, copper also should be metallic. Copper inclosed in iron sulphide, which is also inclosed in metallic iron, may suggest that some of the sulphur was once in combination with the copper, previous to reduction of the metals.

A determination of the specific gravity of two small specimens without metallic veins, weighing 168 and 127 gm. respectively, gave the result 3.76. Specimens with veins would yield a higher specific gravity determination.

Following is an analysis by J. E. Whitfield, for privilege of early publication of which we are indebted to Dr. George P. Merrill, of the National Museum:

	Percentage
Metallic portion	19.90
Silicate portion	80.10

The metallic portion yielded as follows:

	Percentage
Fe	90.89
Ni	8.92
Co	0.15
P	0.04
	100.00

The silicate portion yielded:

	Percentage
SiO_2	44.49
TiO_2	0.10
Al_2O_3	2.46
Cr_2O_3	0.64
Fe_2O_3	4.34
P_2O_5	None
MnO	0.19
FeO	16.23
CaO	2.69
MgO	28.32
Na_2O	0.85
K_2O	0.165
	100.475

These analyses were made from fragments apparently representative of the matrix of the meteorite, but not representative of the vein material. From the absence of sulphur and copper in the analysis it appears that the vein material is generally different from the rest of the stone.

On November 9, 10, and 11, 1919, the following data and evidence were collected at the places noted.

At Mandan, 70 miles east and about 10 miles north of the locality of the fall, several people saw the meteorite. It happened that there were two troop-trains in the yards at the time and any noise the meteorite made was not noticed during the celebration.

At Dickinson, 30 miles northwest of the locality, the meteorite appeared as a bright light which went out suddenly, accompanied by a rushing, roaring sound which seemed to shake the air.

A person interviewed in Richardton was in New Leipzig, about 20 miles southeast of the locality, at the time the meteorite fell. He had just gone to bed when he was startled by a brilliant light, which he took momentarily for the headlight of a locomotive; however, he went to the window and saw a meteorite passing to the west of the town, going apparently in a northwest direction and falling at a low angle. The witness recalled that there was a roaring sound like that of an airship for about two minutes, followed by a violent explosion; it was a fearful and terrifying noise,

rattling the windows and shaking the house severely, resembling an earthquake. To others at New Leipzig it sounded like rolling artillery.

Mr. Bernard Kuntz, Section 27, Township 137, Range 92 west of the fifth principal meridian, saw the fall. To him the flight seemed to be from southwest to northeast, making the countryside as bright as day. He described the noise as like that of an airship or a motorcycle. He found several specimens.

Mr. Nickolas Kuntz lives on another quarter of the same section as Bernard Kuntz. All his family were in bed and asleep at the time, but they were awakened by the light and noise, which they took to be caused by lightning, thunder, and rain. Mr. Kuntz found one boloid weighing 11½ lbs., which was in a shallow hole on plowed land; another weighing 2 lbs. 10 oz., which was lying on the surface in a pasture; and a third weighing about 9½ lbs.

Mr. Rochus Steiner, living in the northwest quarter of Section 26, Township 137, Range 92, made a written record of the fall. According to his notes it was 10:39 P.M., Sunday, June 30, 1918. He noticed first a bright light for one-half minute; then there came a sound like rolling thunder which shook the windows of the house, followed by a whistling like that of a bullet. He found a broken meteorite partly buried 5 or 6 inches in the loose earth at the roadside, the pieces weighing about 6¾ lbs.

Mr. Leo Kern, Section 18, Township 136, Range 92, saw the fall. He was walking home about 10 o'clock at night, when suddenly there was a bright light. At first it was like a bright shooting star; then it became a streak of fire until it burst like a Roman candle. It appeared to be coming from the southeast, falling at an angle of about 15° to the horizontal. It made a "rattling sound like an airship," and when it burst the earth all about him trembled, and the house shook with the violence of the explosion. He prudently took shelter behind a telegraph pole, as the meteorite appeared to be coming directly toward him. After the explosion he heard pieces flying through the air like whistling bullets, and pieces rattled against the roof of his barn, where he found some later. After the meteorite had burst there

appeared to be a trail of "smoke or steam" in the line of flight. Several specimens were found by his daughters, Misses Emma and Irene Kern, and contributed by them to the collection of the University of Minnesota.

Mrs. Nell F. Rodenbour, postmistress at Lemmon, South Dakota, writing February 25, 1919, describes the fall as follows:

> I saw this meteorite myself and can only describe it thus: At about 11 o'clock at night we heard a dull roar like thunder, and we all ran out of the house to see, and there appeared a bright flash of light across the whole sky. It fell to the northwest, more north, and left a tail of light which remained for fully fifteen minutes.

Lemmon is about 45 miles south and 8 miles east of the place where most of the meteorite fell.

Mr. N. R. St. Marie, of Hettinger, North Dakota, wrote on February 27 as follows:

> The writer was lucky enough to get an almost perfect view of the meteorite. I was seated in an auto sky-gazing, when it attracted my attention as a shooting star. In a moment I saw that it was out of ordinary. Starting from very high it fell rapidly earthward, a little to the east of north, about 10 or 15 degrees, I judged. As it came down it illuminated the landscape to almost the brilliancy of sunlight, but the light was first of a green and later of a yellow hue. A faint whistling was discernable to part of our party; others, however, said they didn't notice any sound.
>
> I was 65 miles south and 15 miles west of Hettinger at the time.

In answer to further inquiry, on March 1, 1919, Mr. St. Marie added:

> I first noticed it very high in the heavens giving the appearance of being nearly over me; as it approached the earth it appeared more and more to the northeast.

This observer was 100 miles south and 30 miles west of the locality of the fall at the time.

Mr. Lewis Loran, Section 33, Township 137, Range 92, found several specimens of the fall, and was a witness of the phenomena. On December 12, 1918, he wrote the following detailed description of the fall:

> It was June 30, at 10 P.M.; my wife and I were in my yard, and I looked at the sky and I discovered the meteor. It was as large to me as about two

inches in diameter, and it was just where the sun is about the first week in November at fifteen minutes after twelve. It came nearer and nearer, and larger and larger, so at last I thought I must go out of its way or it would strike me. It was at least as big to me as the sun is sometime in August when it sets, but more than three times as light; then it flashed out (it was a cloudless night and no wind), and it was all still. I said to my wife, "Where is it now? It has to come. It is so near to the surface of the earth." It just took this long to say these words when we heard a great racking in the air in the same direction, and in a few seconds we heard the pieces sounding through the air like shells. We could hear that there were some smaller and some larger pieces, and that some went beyond us and some fell south of us. But the worst racking and noise was the exploding in the air. It seemed that it shook the ground under my feet, and I could hear the windows in my house rattle. We could not see the pieces, but we could hear them, and we could tell that they came from the direction from which the meteorite came.

The light of the meteor was seen over more than 400 square miles, and the noise was heard over 250 square miles.

The following account of the fall was written by Mr. Orris W. Roberts, meteorologist, United States Weather Bureau, Bismarck, North Dakota:

This meteorite was observed by the writer. I was driving my automobile some distance east of Bismarck on the night in question. As we make reports of such phenomena I am in position to give some information. The time of observation was 10:48 P.M., June 30, 1918. The meteorite appeared to move somewhat north of east and the explosion was plainly to be seen, although no report reached the observer. The light was intense, lighting up the entire sky. . . . . The location of the meteorite at the time of the explosion as located on our reports would indicate that it occurred over eastern Hettinger county.

Writing on March 19, 1919, Mr. Roberts recalled that the meteorite appeared to be falling at an angle of less than 45° to the horizontal. Bismarck is 74 miles east and 10 miles north of the locality where the meteorite fell.

There is apparent a discrepancy of about an hour between the time of fall as given by Mr. Roberts, a trained observer, and that given by almost all the other witnesses. The explanation is that Mr. Roberts, stationed at Bismarck, uses Central time, whereas the other observers quoted live west of the Missouri River, which is the geographical boundary between users of Central and Mountain time in that latitude. Mr. Roberts' estimate that

the explosion occurred over eastern Hettinger county is shown by other witnesses to be correct. The green light noted by Mr. St. Marie may have been caused by the presence of copper in the meteorite. Mr. Loran's estimate of the area over which the meteorite was seen and heard is low, because it must have been seen at a distance of one hundred miles in every direction, and the sound was heard at least fifty miles from the place of fall.

One who has read the descriptions of other meteorite falls may recognize a notable expansion with the times in the language of the witnesses. Doubtless the phenomena have been generally similar. There have been a streak of light, the noise of disruption or merely of the swift passage of masses through the air, and in some instances the whistling of smaller pieces. In early descriptions the witnesses compared the noises almost exclusively to thunder and the rolling of wagons; later came comparisons to the roar of artillery fire or the rumble of cannons, then to noises like a railway train, and to the sound of a train of cars on a bridge. The Modoc fall in 1905 perhaps is the first to have been compared to the noise of machine-gun fire, but in the descriptions of the Richardton fall the noises of small pieces are compared to that caused by the flight of shells and bullets; whereas, to describe the general noise of the fall, the witnesses introduced in comparison the motorcycle and even airships.

The Richardton meteorite is the third to be reported from North Dakota, the others being two iron meteorites: (1) at Jamestown, Stutsman County, weighing originally 4,015 gm., found in 1885, date of fall unknown; and (2) at Niagara, Grand Forks County, weighing 115 gm., found in 1879, date of fall also unknown. Richardton is the only fall which has been reported as seen to fall in North Dakota, and it is by far the largest found in the state. Of the three meteorites, the only one preserved in collections of the state is Richardton. Two representative boloids, weighing 2 lbs., and 12 oz., respectively, are at the state university. Both the Jamestown and the Niagara meteorites are widely distributed throughout the collections of the world. In this connection it may be urged that finders of meteorites should try to have a representative of every fall placed on exhibition some-

where, preferably at the state university museum, within the state in which it fell. In this way some of the public would become familiarized with meteorites, their general appearance, and their nature. The work of the collector and scientific investigator would be lightened if the finders of meteorites could be deterred from believing that meteorites contain gold, silver, platinum, radium, and other rare metals in large quantities, and from investigating meteorites with sledge hammers.

With the help of Professor W. O. Beal, of the department of astronomy of the University of Minnesota, the azimuth and vertical angle of the fall of the meteorite have been computed, using the description of Mr. Loran.

In Mr. Loran's position at 12:15, the true local time is 12:45 P.M., at which time the sun is 12° W. of S. In his latitude on the seventh day of November the sun is at an elevation of 27° above the horizon at noon. Thus, according to Mr. Loran the meteorite fell in a direction 12° E. of N., making a vertical angle of about 27° with the earth's surface.

Mr. St. Marie, 100 miles to the south and 30 miles west of Mr. Loran, thought the meteorite started to burn immediately above him. His bearing from Mr. Loran was 17° W. of S., showing that Mr. Loran's estimate of 12° W. of S. must be nearly correct. Furthermore, Mr. St. Marie estimated the direction of flight as from 10° to 15° E. of N. Mr. St. Marie and Mr. Loran were 104½ miles apart at the time of their observations, representing the locations of the incipient incandescence and the landing of the meteorite. If the meteorite fell in a straight line the altitude of the meteorite when it started to burn was at least 54½ miles above the earth's surface, allowing 1½ miles for the earth's curvature. This height should be increased probably to at least 60 miles because the meteorite probably did not fall in a straight line, but rather in a parabolic curve, although there are no data recorded about that except Mr. St. Marie's note that the meteorite appeared to fall progressively more toward the east. It seems safe to say that the meteorite started to burn at a great, but not an unusually great, height above the earth. Heights of 40 and 100 miles bound the region in which meteorites commonly start to burn.

At a height of 60 miles above the earth the air is extremely thin, indicating that the meteorite entered the atmosphere at a very high velocity, otherwise it would not have developed enough friction with the air to cause combustion. The meteorite fell near latitude 46° 30′, in June, at approximately 10 P.M., at an angle of 27° to the surface, going northward, from which data it follows that the meteorite was falling toward the sun when it was intercepted by the earth. Falling at an angle of about 90° to the course of the earth, the meteorite entered the earth's atmosphere at neither the highest nor the lowest velocity possible relative to the earth. In other words it fell neither directly opposite to the earth's flight, the condition of maximum velocity, nor did it catch up with the earth, a condition of minimum velocity. However, a meteorite falling toward the sun at the distance of the earth's orbit commonly has a velocity of 25 miles per second. By the earth's attraction the velocity might have been increased to 30 miles per second. It seems a conservative estimate to call the velocity of the meteorite when it entered our atmosphere about 30 miles per second.

The general unbroken condition of most of the examples of the fall, in spite of their brittle nature, indicates that the meteorite struck the earth's surface at a relatively low velocity. It is not clear why a meteorite should become incandescent in a very tenuous atmosphere, 60 miles above the earth, and then why its broken fragments after disruption in much denser air should not burn, unless the velocity is decreased enormously during its passage through the air. The meteorite must have passed through at least 117 miles of air from the time it commenced to burn until it reached the earth. This thickness of atmosphere appears to have offered enough obstruction to the passage of the meteorite to reduce the velocity from probably about 30 miles per second to something much less. All this, of course, is quite in accordance with commonly accepted notions as to the general behavior of meteorites. If anything, the height at which the meteorite is estimated to have commenced to burn is somewhat low for the velocity postulated. However, the general probability of the conclusions reflects most creditably upon the accuracy of the observations of both Mr. Loran and Mr. St. Marie.

Although after explosion it seems that the meteorite was not incandescent, it certainly was fused additionally; for all the surfaces freshly exposed by the main disruption were completely fused over by the time the fragments reached the earth. To such an extent was that accomplished that it is not quite certain to the writer that all the material discovered entered the atmosphere as parts of a single mass. Many of the smaller pieces, particularly, appear as if they may be units of a shower. Among the smallest pieces certain specimens show clearly three degrees of fusion. All the specimens from the northern part of the locality are covered with a thick, well-fused crust. Only the small pieces from the southern part of the area have slightly fused surfaces. These small pieces went through at least 5 miles less of the atmosphere than the thoroughly fused pieces, and some of them, at least, are fragments of a second disruption which must have occurred very near the earth. Presumably the small pieces fell first because they offer more areal resistance to the atmosphere per unit mass than the larger pieces.

Unquestionably atmospheric obstruction is responsible for the fusion and disruption of the meteorite. Disruption is commonly ascribed to shock of impact with the air, and to the disruptive effect of heat. The heat, however, probably penetrates a very little distance beyond the crust of actual fusion and combustion, and the character of meteorite ruptures certainly is not like that due to the spalling of heated surficial masses. In most cases meteorites are broken through the main mass, rather than shelled off in the familiar manner of insolation spalling of massive rocks. In the case of the Richardton meteorite, rupture was facilitated in places by the presence of metallic and troilite veins, which are planes of weakness. Several specimens are bounded partly by more or less fused metallic vein matter.

The question arises as to why the light of the meteorite ceased with its disruption. The disruption of the meteorite is described as an explosion, but this is probably a poor choice of words. There is apparently nothing in the meteorite capable of causing an explosion; but if it had exploded, part of the mass would have continued at a higher velocity relative to the air and part at a speed less than that previous to its explosion. The fact is that

the light ceased after disruption, proving that the velocity was lessened rather than increased, and indicating that the meteorite fell apart but did not explode. Such a disruption, of itself, should not decrease the velocity of flight, and except for the influence of the larger surfaces exposed, before noted, the meteorite fragments should have continued to burn after disruption as before. The fact that they did not burn again indicates that the velocity of the meteorite was so decreased at the time of disruption that the exposure of intensely cold surfaces from the interior of the meteorite, added to the increased damping effect of the atmosphere on larger surfaces, was sufficient to prevent the intense temperatures necessary for burning. Thereafter, the velocity of the meteorite must have decreased progressively as it entered denser and denser air until it reached the surface. Although not heated enough by this obstruction to burn brightly after disruption, the meteorite certainly was heated enough to cover the larger pieces with a heavy fused crust, and to form a thinner crust on the smaller pieces. The smaller pieces had a thin crust both because they went less rapidly than the larger pieces through the air, and because they went a shorter distance through the atmosphere after disruption.

Many residents of the district in which the meteorite fell have assisted greatly in collecting data and specimens. In addition to those especially mentioned above, Mr. John Muggli, of Richardton, has extended many courtesies and has given much help. Mr. W. A. Force, of the Photo Art Shop, Minneapolis, has given of his time and experience in securing the photographs from which the illustrations are made. Funds and opportunity to investigate the phenomena of the fall and to collect specimens for the museum were provided by the University of Minnesota.

A new fall has been named, classified, and described. The phenomena of fall have been reported more fully than usual, and certain conclusions in regard to the direction of flight, velocity, and consequences of disruption of the meteorite seem to follow reasonably. The meteorite is noteworthy for the concentration of metallic iron and nickel and iron sulphide in veins. The discovery of visible, metallic copper in a meteorite is announced.

PRE-CAMBRIAN ROCKS OF SOUTHEAST NEWFOUNDLAND[1]

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The following paper gives the more important results of an investigation based upon field work carried on during the summers of 1913 and 1914.

Southeastern Newfoundland is important geologically in that it affords, as far as is known, the most complete section of the later pre-Cambrian rocks along the eastern coast of North America, and an understanding of this section should aid in the correlation of the later pre-Cambrian at other localities. The term later pre-Cambrian, as here used, is possibly the equivalent of the terms Proterozoic or Algonkian.

LOCATION AND GEOGRAPHY

The Avalon Peninsula (Fig. 1) forms the southeastern portion of Newfoundland and is attached to the main island by a narrow, rugged isthmus, in places but three miles wide, which separates Trinity Bay on the north from Placentia Bay on the south. The peninsula itself is in turn almost split in twain again by St. Mary's and Conception bays. The major portion of the rocks here described lie along the eastern side of Conception Bay, at the head of this bay, and in the vicinity of St. John's; but they are believed to be typical of the entire peninsula and of the later pre-Cambrian rocks of eastern Newfoundland in general.

Except for the mining industry conducted on a large scale at Great Bell Island in Conception Bay, fishing is almost the sole occupation of the inhabitants. As a consequence of this and of the unfavorable character of the interior of the peninsulas, habitations

[1] Thesis presented to the faculty of Princeton University for the degree of Doctor of Philosophy.

are confined almost exclusively to the shore lines, and often to small valleys at the mouths of brooks which may be from a fraction of a mile to several miles apart.

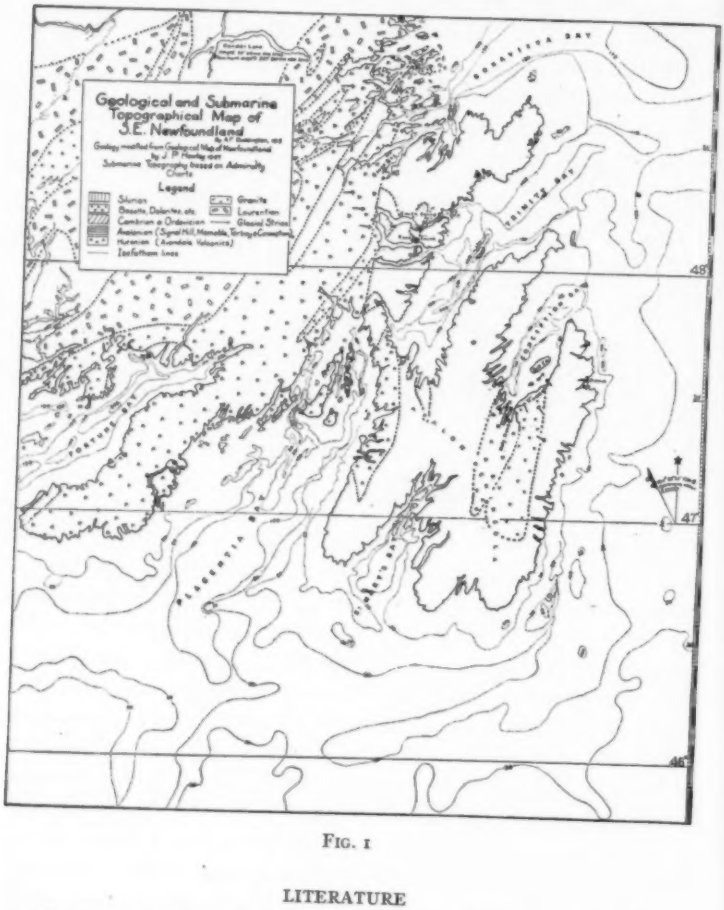

FIG. 1

LITERATURE

The literature on Newfoundland pre-Cambrian geology is well summarized by Van Hise and Leith (1909). Jukes (1843, p. 51) first separated the Cambrian from the pre-Cambrian and noted the

unconformity existing between them. He was followed by Murray (1881), who gives accurate descriptions of the pre-Cambrian sediments and classes them as the intermediate series, possibly equivalent to the Huronian of Canada. Walcott (1899, p. 219) proposed the name Avalon for the terrane lying between the basal beds of the Cambrian and the Archean gneisses of Newfoundland. Walcott (1900) described a new pre-Cambrian terrane conformable above the Signal Hill series, which he called the Random and included in the Avalon terrane. Howley (1907) published a map in which he outlined the distribution of the Avalonian series and also distinguished a formation composed of interbedded volcanics and aqueous deposits, which he separated from the base of the Avalonian terrane and called Lower Huronian. The succession worked out by Murray and Howley, the addition by Walcott, and the modification proposed by Howley are given below.

		Feet
Random	Sandstones, quartzitic sandstones, and sandy shales	1,000
Signal Hill	Red conglomerate	500
	Dark-red sandstones	1,320
	Greenish or gray fine-grained sandstones	1,300
Momable slates	Dark-brown or blackish slates	2,000
Torbay slates	Green, purple, pinkish, or red slates	3,300
Conception slates	Greenish slates	
Lower Huronian	Mixed igneous and aqueous deposits in a highly metamorphosed condition	

PHYSIOGRAPHY

In general, the striking features of the Avalon Peninsula are the parallel lineaments of the topography; the ever-present, bold, rocky cliffs of the coast; the flat-topped uplands with innumerable lakes and ponds (Jukes counted 153 from the top of Powder Horn Mountain); and the fiord bays with their deep interiors and shallower thresholds.

The topography is that of a much-dissected plateau at an altitude of from 500 to 700 feet, with monadnocks rising to heights of 1,000 to 1,100 feet, and submerged river valleys deeply gouged by glaciers and invaded by the sea, constituting fiord bays and their arms. The remnants of two definable peneplains may be represented in the present topography: one on the highland peneplain

of the plateau surface (Fig 2), the other represented in the broad river valleys and lowlands at a height of 250 to 300 feet.

The trend lines of the more impressive and marked physiographic features have been controlled for the greater part by the presence of ancient fault and fracture lines, which have to a large extent determined the distribution of the underlying rocks, with their varying degrees of resistance to erosion and weathering and the consequent parallel lineaments of the present topography. Joints have certainly played a prominent part in localizing the erosive agents.

FIG. 2.—Highland peneplain on granite; interior of the St. John's Peninsula; about eight miles east of Holyrood.

An uplift of the land following the period of glaciation is indicated by several facts. The amount of this uplift has been stated by Daly (1891, pp. 257–58), judging from the lower limit of undisturbed glacial erratics at St. John's, to be about 575 feet; but the presence of perched bowlders in precarious positions on the tops of hills at much lesser elevations (especially at about 300 feet) around Conception Bay renders this estimate of doubtful value.

GLACIATION

The results of glaciation expressed in the present topography point to the presence of local ice caps flowing into the individual bays in a direction perpendicular to the major outlines of the bays

at each point, and hence controlled in a great degree by the gross features of the pre-glacial topography. The directions of ice movement are easily decipherable from the abundant striations, the stoss and lee sides of hills (Fig. 3), and numerous bowlder trains which may be traced to their source.

Every bay indenting the coast of the Avalon Peninsula presents all the essential characteristics of a fiord, such as high, steep, straight, parallel walls, threshold across its mouth, and small, insignificant streams entering its head. In Trinity Bay (Fig. 1) the inner, deepest portion is over 1,100 feet deeper than the sill across the mouth. Where the relations are known there is a remarkable parallelism between the strike of the major fault planes and

FIG. 3.—Glaciated hills with lee and stoss sides southeast of Harbour Main, Conception Bay. Lee sides are on the north-northeast ends of hills.

the trend of the coast line, but the writer could find no evidence that faulting was directly responsible for the formation of the fiords. The faults and fractures controlling the lineaments of the bays are of ancient date—older than the peneplains—and their influence on the present topography has been indirect. The formation of the sills across the mouths of the bays by deposits from currents is improbable, since this theory will not hold for the inland fiords of Gander Lake, Red Indian Lake, or Grand Lake, the latter with its deepest part not less than 988 feet below sea-level and with its outlet 116 feet above sea-level. In view of these conditions glacial overdeepening of river valleys probably associated with some submergence followed by the invasion of the sea seems the best-adapted explanation for these fiord bays

GENERAL GEOLOGY

The later pre-Cambrian beds have undergone at least two periods of folding, one at the close of the later pre-Cambrian, possibly the Penokean revolution, as defined by Blackwelder (1914), the other the Taconic. As a consequence of this, and of probable later movements, the beds are much disturbed, more or less closely folded, and very considerably faulted. The core of a major anticline composed of complexly faulted and folded beds of the volcanic series, cut across at a small angle by a stock of granodiorite, is exposed at the head of Conception Bay. At Chapel Cove its eroded surface is overlain by beds constituting the south end of a northward-pitching synclinal fault block of Cambrian sediments, in which Conception Bay is excavated. We have here apparently the phenomenon of the location of a younger syncline in sediments deposited in a basin on the eroded crest of an anticline.

Cutting across the east flank of the anticline is a batholith of granite forming the backbone of the St. John's Peninsula and called by the writer the Holyrood granite batholith. This is bordered on the east by a narrow band of the volcanics overlain by successively higher beds involved in minor folds until the trough of a major syncline in the Signal Hill series is reached east of St. John's. According to Murray and Howley's map of 1881 the Carbonear Peninsula is formed of later pre-Cambrian beds which overlie the volcanics and are involved in two major synclines in the troughs of which the Signal Hill series appears, with an intervening anticline on the core of which the Torbay series appears. The Placentia Peninsula, according to the same map, is composed of a syncline of beds in the trough of which the Signal Hill series lies, while the volcanic series forms its western border and appears on the flank of an anticline.

Metamorphism, although not extreme, has yet affected the rocks to a considerable degree. The beds lie in folds which, although probably not closed, yet approach that state, and a slaty cleavage at an angle to the bedding is prevalent throughout the entire bedded series. Along localized zones basaltic flows and breccias have been changed to chloritic schists, and rhyolite flows have been analogously altered to pinite, quartz-pyrophyllite, or pyrophyllite

schists (Buddington, 1916). Yet the granite, granodiorite, and many of the volcanics show little or no affects of metamorphism and are quite unaltered.

Whereas metamorphism has been a moderate factor, however, faulting on a tremendous scale and often of remarkable intensity has been the predominating feature of the diastrophic processes. These faults trend in the main a little east of north, and the throw along many of them is measurable in thousands of feet. A few of the more important ones are the fault between the Cambrian and pre-Cambrian along the east side of Conception Bay from Topsail to Cape St. Francis, with a throw of 8,000 feet, as determined by van Ingen; the fault a short distance inland from the west side of Colliers Bay in Conception Bay, which may be traced for almost ten miles and separates the Cambrian from the pre-Cambrian and the Conception slates from the volcanic series; and lastly, the fault on the west side of Random Sound, which may be traced for fifteen miles and brings Cambrian beds against pre-Cambrian granite and the Conception slate series.

UNCONFORMITY BETWEEN CAMBRIAN AND LATER PRE-CAMBRIAN

The uncomformable relations of the Lower Cambrian beds to those of the later pre-Cambrian, with the possible exception of the Random formation, can be definitely established. At eleven widely separated localities in Conception Bay the actual unconformable plane of contact between the Lower Cambrian and the later pre-Cambrian may be observed.

At Brigus the Lower Cambrian rests with an angular unconformity on the upturned beveled edges of members of the Avondale volcanic series. Along Colliers Bay the Lower Cambrian with a gentle dip rests unconformably on more or less vertical basalt flows and breccias of the Avondale volcanic series. At Chapel Cove the Lower Cambrian beds rest on the eroded surface of a quartz syenite and contain pebbles of the underlying rock. At Duff's Station the Lower Cambrian overlies granite, occupying hollows and filling deep, narrow wedgelike spaces between joint planes so as to resemble a network of veins on the surface. At Upper Gullies it rests with unconformable relations on a gabbro mass. On Kelligrews Brook

a chloritized granite gneiss is overlain by Cryptozoan limestone beds of Lower Cambrian age. Just west of Manuels three exposures of the unconformable relations are presented. At the first locality limestone rests unconformably on granite and on a rhyolite dike in the granite. A shale bed of Cambrian age overlaps the limestone and also rests directly on the granite and contains pebbles of it. A near-by conglomeratic limestone consists almost entirely of cobbles of rhyolite similar to the rock of the rhyolite dike. At the second locality a deep-fissure deposit of conglomeratic limestone with pebbles of the country rock occurs in diabase. At the third locality a Lower Cambrian conglomeratic limestone carrying Hyolithes and Coleoloides rests on dark-red rhyolite, the pebbles consisting almost entirely of the underlying rock. Again, in the bed of Manuels Brook a coarse conglomerate rests unconformably on volcanics and on a granite dike intrusive in the volcanics. The conglomerate is of Lower Cambrian age and consists of cobbles and bowlders of the underlying granite and volcanics.

On Trinity Bay, along Smith and Random sounds, the Lower Cambrian, of older age than that on Conception Bay, rests disconformably on beds of the Random formation in the trough of a syncline. The Random may be either conformable or disconformable with the Signal Hill series. In either case the Lower Cambrian must be unconformable with the Signal Hill series and all lower formations, since it must necessarily have transgressed all the later pre-Cambrian formations in passing from its disconformable position on the Random, the youngest formation of the pre-Cambrian, in the trough of a syncline, across the flank of an anticline on to the lowest later pre-Cambrian formation, the Avondale volcanics, on the core of an anticline in Conception Bay.

AVONDALE VOLCANICS

Howley (1907) mapped a series of rocks which he called Huronian and described "as composed of mixed igneous and aqueous deposits in a highly metamorphosed condition." Parallel to their trend they are mapped by Howley as outcropping for a distance of about two hundred miles in a north-northeast-south-southwest direction, being submerged beneath the sea at each end.

In view of the unknown age of this formation, and because of its characteristic development and typical outcrops in the vicinity of Avondale, Conception Bay, the writer proposes the name Avondale volcanics to designate this series, which comprises rocks of direct volcanic origin, together with a small amount of interbedded more or less waterworn volcanic materials. They constitute a formation of wide geographical extent—200 miles along the strike and 100 miles or more across the strike—and of great but unknown thickness, at least several thousand feet, forming so far as is known the basal member of the later pre-Cambrian or Avalonian system of Newfoundland. Interbedded rhyolite and plagioclase basalt flows, with corresponding breccias, crystal, lithic, and vitric tuffs, volcanic dust beds, and average tuffs, together with volcanic conglomerates, sandstones, and slates are comprised within the series.

The beds are in a highly disturbed condition, with a prevailing steep dip, and are affected by intense and often profound faulting. They are exposed on the cores of major anticlines or are brought to the surface on the upthrow sides of great faults. The degree of metamorphism which the rocks have suffered is in general moderate, though locally intense, and is manifest for the larger part merely in the development of a slaty cleavage. Secondary minerals, except those of surface origin, are confined almost exclusively to sericite and quartz in the acid rocks and chlorite with sericite, epidote, and calcite in the basic rocks. Along certain shear zones in the acid rocks pyrophyllite, quartz-pyrophyllite, and pinite schists have formed through replacement, while in certain basic rocks copper ores have been deposited along close-set narrow fractures and in vesicles of the flows. Ore in quantities of commercial importance, however, has not yet been found.

In view of the great age of the rocks the lack of intense metamorphism and the frequent preservation of delicate primary structures are striking. Indeed there is little doubt that, with search, practically every structure and texture found in the Tertiary and recent volcanics might also be found in these ancient pre-Cambrian volcanics.

One of the most interesting discoveries in this series was the presence of volcanic necks intruded through the breccias and tuffs.

Near Manuels a plug of plagioclase basalt about 400 by 450 feet, with columnar jointing perpendicular to the surface and with dikes and apophyses radiating from it into the adjoining rocks, was found intruded through basaltic and rhyolitic breccias. A rhyolite neck about fifty feet in diameter and circular in shape, nearly every foot of the contact of which could be seen, and a neck of basic tuff with fragments up to three feet in diameter of the underlying rocks, through which it was drilled, and with radiating dikes of tuff, were also found. The largest neck forms a conspicuous hill about three miles south of Holyrood and seems to have been one of the main centers of volcanic activity in this region. Here we find a great elliptical stock of rhyolite porphyry about a mile long and half a mile wide, while in the surrounding country occur exceptionally coarse rhyolite breccias, with many blocks up to two feet in diameter, interbedded with rhyolite flows and tuffs. A chemical analysis of this rock, given below, shows it to be very similar to the rhyolite flows at Manuels.

TABLE I

CHEMICAL ANALYSIS OF RHYOLITE PORPHYRY FROM VOLCANIC NECK SOUTH OF HOLYROOD

SiO_2	75.85	K_2O	4.47
Al_2O_3	13.03	H_2O+	.35
Fe_2O_3	1.82	H_2O-	.05
FeO	.32	MnO	.05
MgO	.05		
CaO	.38	Total	99.71
Na_2O	3.34		

The rhyolite flows are quite variable in color, ranging through reddish, purplish, and greenish grays. They are usually aphanitic in texture, and dense, chertlike in character, sometimes felsitic, with a finely rough feel. They may be homogeneous and massive, or may be marked by beautiful, well-developed, and well-preserved banded textures, and are very frequently spherulitic. The spherulites vary from microspherulites up to those as large as a man's head, or even occasionally attain a diameter of two feet (Fig. 4), but in general they are of medium size (Fig. 5). The flows may also be characterized by a platy jointing more or less parallel to the flowage planes, or by flow breccia, eutaxitic (Fig. 6), or perlitic structures.

As seen in thin section the texture is usually microgranitic or an irregular polarizing aggregate of quartz and feldspar. Spherulitic, axiolitic, and microspherulitic textures are common, and rarely a felt of microlitic feldspars in a groundmass of quartz is observed. A micrographic texture characterizes portions of an eutaxite from

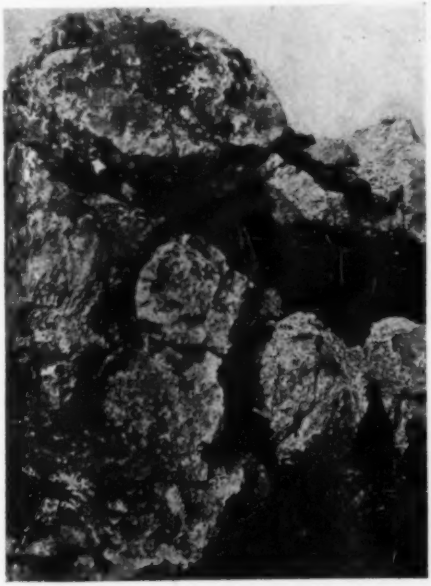

FIG. 4.—Very coarsely spherulitic rhyolite; the largest spherulite is twenty-two inches in diameter; about five and one-half miles south of Manuels, Conception Bay.

near Avondale. A chemical analysis of a specimen from a 50-foot rhyolite flow follows. The rock is a dense, red, banded felsite with a microfelsitic to finely microcrystalline and micropoikilitic texture.

TABLE II

CHEMICAL ANALYSIS OF RHYOLITE FROM FLOW AT MANUELS

SiO_2	76.24	Na_2O	2.55
Al_2O_3	13.94	K_2O	4.95
Fe_2O_3	.89	H_2O+	.15
FeO	.13	H_2O-	.03
MgO	.27		
CaO	1.07	Total	100.22

FIG. 5.—Medium spherulitic banded rhyolite; about five and one-half miles south of Manuels, Conception Bay. Photograph by G. v. I.

FIG. 6.—Microphotograph of eutaxitic structure in rhyolite. Hill 467, south of Avondale, Conception Bay. Natural light, ×32 diameters.

Basalts attain a tremendous development along Colliers Bay, extending south toward Brigus Junction. They are associated with a great development of basaltic breccias and often exhibit amygdaloidal or flowage structures. The flows are very much altered throughout and may be chloritized with resultant green-gray rocks, or hydrated and thoroughly impregnated with iron oxide giving purplish- or reddish-brown hues. These alterations are probably due to thermal waters, as they occur independent of what

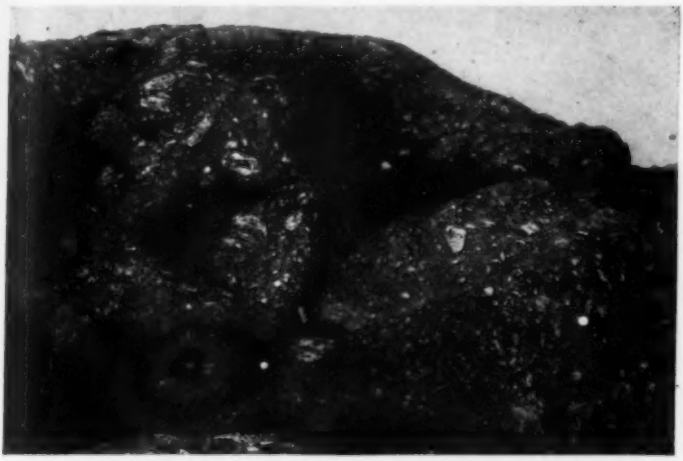

FIG. 7.—Coarse rhyolite breccia; about two and one-half miles south of Manuels, Conception Bay. Photograph by G. v. I.

might be expected as the result of weathering. In texture they vary from felsitic to finely porphyritic, and in thin section show a felt of plagioclase laths or microlites with a distinct fluxion structure in a chloritic or indistinct altered groundmass. Chlorite pseudomorphs, replacements of some ferromagnesian mineral, possibly augite, occur as abundant minute phenocrysts in some flows.

The breccia beds exhibit a varied assortment of colors and a wide range in the diameter of their component fragments; but by far the predominant portion of the rhyolitic breccias are various hues and tones of reddish- and purplish-gray, whereas the basaltic breccias

consist of dark greenish-gray fragments in dark reddish-, purplish-, or greenish-gray matrices.

Both basaltic and rhyolitic breccias exhibit approximately the same range in the diameter of their fragments, from a fraction of an inch to four feet (Figs. 7 and 8). The general run of the fragments

FIG. 8.—Coarse basalt breccia; west side of Blue Hills, south of Conception Bay

would probably average a few inches in diameter. In general, the rhyolitic breccias and the basaltic breccias contain few foreign fragments, especially the coarser beds; yet beds in which angular fragments of rhyolite and basalt and crystals of orthoclase and plagioclase are mingled are frequent; and rhyolitic breccias and basaltic breccias are often found interbedded.

Crystal tuffs are of frequent occurrence interbedded with the breccias and tuffs. They are remarkable, in view of their great age and the vicissitudes which they have undergone, for the frequent presence of a perfectly preserved vitroclastic structure in their groundmass, whether rhyolitic or basaltic in nature. These devitrified glass shards are such a prominent feature of some of the tuffs from the vicinity of Red Rock Lake near Brigus that they

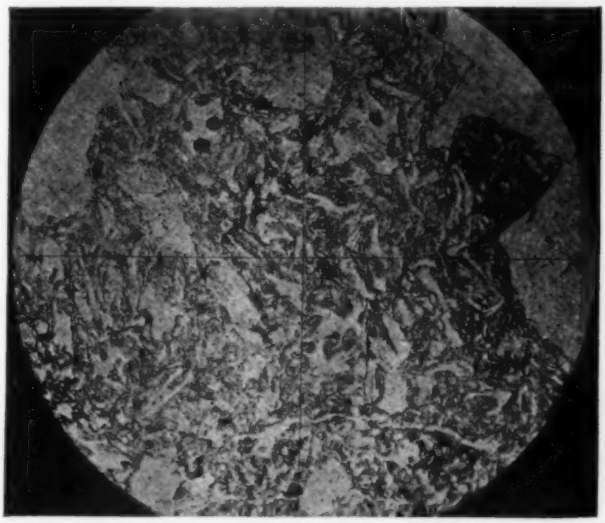

FIG. 9.—Microphotograph of vitroclastic groundmass of rhyolitic crystal tuff; near Red Rock Lake, south of Brigus, Conception Bay. Natural light, ×56 diameters.

might well be denominated vitric tuffs (Fig. 9). In other cases the groundmass is an indistinct, microcrystalline, granular dust. Many of these tuffs are soaked with hematite and hence are reddish in color. Associated with the phenocryst-like crystals are fragments of either porphyritic or felsitic basalt or rhyolite, or of devitrified obsidian exhibiting trichites, microspherulites, spherulites, axiolites, perlitic cracks, pumiceous structure, or any combination of these. The crystals consist principally of plagioclase and

orthoclase, with quartz and magnetite in the acid tuffs, and of plagioclase, augite, magnetite, apatite, and foreign crystals in the basic tuffs. Some of the basic tuffs resemble typical palagonite tuffs (Fig. 10).

The lithic tuffs consist predominantly of fragments of rhyolite or of pilotaxitic basalt, according to their nature, in a groundmass

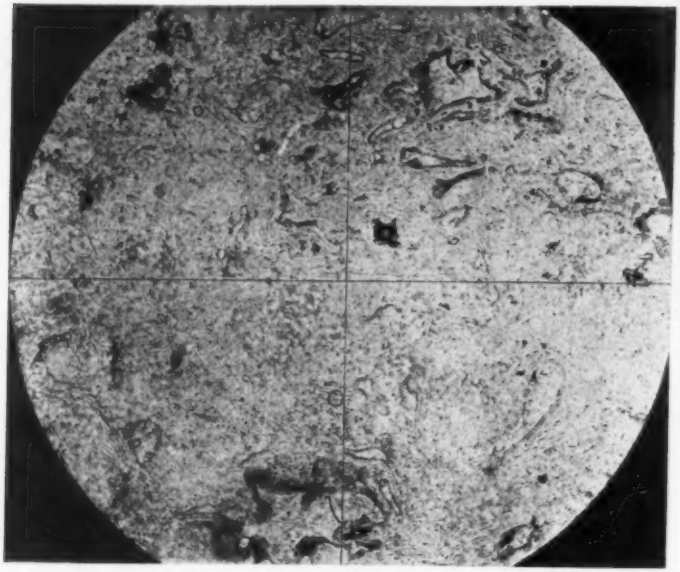

FIG. 10.—Groundmass of basaltic crystal tuff, with devitrified shards of glass bordered by rims of fibrous, brownish material. Hill 937 near Holyrood. Microphotograph. Natural light.

consisting of finely comminuted materials similar to the lithic fragments, with crystals of feldspar and quartz in minor amount. The volcanic-dust beds are frequently well bedded and chertlike in character, often translucent in thin edges, with a conchoidal to subconchoidal fracture.

The waterworn volcanics comprise volcanic conglomerates, sandstone, and a rare red shale bed. The prevalence of volcanic

conglomerates, both stratigraphically and geographically, interbedded with the volcanic breccias, flows, and tuffs, is one of the most cogent arguments for the subaërial origin of the volcanic series as a whole; for both basalt and rhyolite conglomerates are associated with and interbedded between completely angular basalt breccias and well-rounded basalt conglomerates, and between similar angular rhyolite breccias and well-rounded rhyolite conglomerates. In some of the basalt conglomerate beds bowlders up to three feet or

FIG. 11.—Basalt volcanic conglomerate; Turks Gut, Colliers Bay, Conception Bay. Photograph by G. v. I.

more in diameter are not rare (Fig. 11). Such beds are in places 200 feet thick and grade upward or downward into sandstones or tuffs. Some of the sandstone beds are cross-bedded and contain abundant fragments of red shale constituting typical thon-gallen beds. Others are ripple marked, but these features are rare.

In the course of the work no reasons were found for assuming the volcanics to have had other than an essentially subaërial origin. All the structures and textures of the flows and the characters of the associated volcanic products are compatible with such a hypothesis, while the particular criteria pointing to such a conclusion are as follows:

The predominance and widespread distribution of the red and brown volcanic tuffs and breccias, which owe their color to saturation and cementation with hematite, point toward subaërial exposure rather than toward local effects of volcanic gases.

The constant association of volcanic conglomerates or sandstone with the breccias, tuffs, and flows indicates the work either of river erosion, or wave work, or both. The first seems more probable in view of the constant recurrence of conglomerate beds in the stratigraphic succession, as well as the fact that beds of conglomerate 150 to 200 feet, thick with well-rounded bowlders up to three feet in diameter, are exceptional within marine deposits, even within marine volcanic deposits. On the other hand such conglomerates are commonly found associated with subaërial volcanics of all ages. Those of Newfoundland are such as might be expected to form along river valleys draining a region of great active volcanic cones such as this probably was. Although some of the conglomerates may have been deposited in standing water, the indications are that for the most part they were deposited on a land surface during quiescent periods between successive volcanic outbursts which repeatedly buried them with the products resulting from extravasation and explosion.

The volcanics are, so far as known, the oldest formation of the later pre-Cambrian in this district. They are intruded by granite, and together with the granite are overlain unconformably by Lower Cambrian sediments. The pre-Cambrian volcanics of the Blue Ridge of Virginia and Maryland present similar relationships (Keith, 1892), and in the present state of knowledge it seems probable that in early later pre-Cambrian times a chain of volcanic cones extended from Newfoundland to North Carolina and farther, in a zone more or less parallel to the present coast line.

CONCEPTION SLATE SERIES

The Conception slate series was examined by the writer along the east side of Conception Bay from Portugal Cove to Topsail; along the west side, Colliers Bay north to Brigus; near La Manche on the Isthmus of Avalon; and along Smith and Random sounds on Trinity Bay. Owing to folding, faulting, and covered exposures

the relations of this series to the beds above and below were not seen.

The series consists predominantly of thin-bedded, green-gray, dense, hälleflinta-like slates, at least several thousand feet thick, which may be compact without cleavage, or dynamically metamorphosed, with a resultant well-developed cleavage; and to a lesser extent of green-gray feldspathic sandstones and conglomerates. The slates often resemble at a superficial glance banded flow rhyolites, but occasional sandy layers betray their true origin.

The slates may vary from very fine-grained or dense siliceous quartzites to argillaceous slates, or from dense feldspathic quartzites to chertlike feldspathic slates. Thin, intercalated beds and layers of feldspathic sandstone are common, but the predominant character of the rocks is that of a slate. The feldspathic character of the typical slate and its normally fresh, undecomposed character are shown very well by the two chemical analyses which follow. It will be noted that the soda is in excess of the potash, contrary to the usual rule for sediments derived from well-weathered materials, and that the analyses resemble those of certain rhyolites. The high soda content may be due to plagioclases washed in from basic tuffs.

TABLE III

CHEMICAL ANALYSES OF MEMBERS OF CONCEPTION SLATE SERIES

	1	2
SiO_2	68.92	77.13
Al_2O_3	17.67	14.01
Fe_2O_3	1.43	2.25
FeO	3.48	Undet.
CaO	.85	.64
MgO	1.19	.36
Na_2O	3.01	3.59
K_2O	1.46	1.01
Ign. Loss	1.75	.76
Total	99.76	99.75

1. Feldspathic slate, near Brigus, Conception Bay.
2. Feldspathic quartzite, Robinson's Bight, Random Sound, Trinity Bay.

The sandstones are formed of angular to subangular grains of quartz, fresh plagioclase, orthoclase, rhyolite, plagioclase basalt, and tuffs. The rhyolite fragments exhibit axiolitic, spherulitic, and banded textures.

The conglomerate outcrop near La Manche, and the pebbles, are all of volcanic rocks such as basalt, basalt porphyry, rhyolite porphyry, felsite, etc., imbedded in a matrix showing innumerable flashing cleavage faces of white plagioclase.

Since these beds in their well-bedded and unoxidized characters give evidence of their being deposited beneath a permanent water-level, and since they consist almost exclusively of materials similar to the rocks comprised within the underlying volcanic series of subaërial origin, it is probable that an unconformity exists between the Conception slate series and the Avondale volcanics, and that the former are derived from the latter, at that time a more or less loose accumulation of volcanic ash and breccias which were swept into the sea in a comparatively fresh and undecomposed condition.

TORBAY SERIES

The Torbay series was not studied by the writer. Murray's description of it is inserted here for completeness:

> Green, purple, pinkish, or red slates in frequent alternations; the texture of these slates is generally extremely fine, and in some cases they approach in hardness to jasper or chert. The fracture is often conchoidal, and the imperfect cleavage parallel with the bedding; but in many instances the rock has a good cleavage at right angles to the stratification and is well adapted for roofing purposes. The exposed surfaces weather for the most part a yellowish white.

Some beds seen by the writer on the Isthmus of Avalon strongly resemble banded argillites; cobbles of green and red argillite were also found in the drift of the St. John's Peninsula, presumably derived from the Torbay series.

MOMABLE SERIES

These beds are described by Murray (1881, p. 145) as follows:

> Dark brown or blackish slates of St. John's, with ripple marks very distinctly displayed on some surfaces, and in which some obscure organic remains have been found resembling those found in c, and another supposed to be the shelly casing of some description of Annelid. The cleavage of this slate is sometimes very regular, oblique, or at right angles to the bedding, but in parts it also cleaves parallel with the stratification. Towards the top are frequent layers of hard, fine-grained, greenish sandstone interstratified, not usually over 6 or 7 inches in thickness.

The beds seen by the writer are strongly ripple-marked, blackish-gray, thin-bedded, very fine-grained, shaly sandstones, with thin films of black carbonaceous or graphitic shale. In thin section the sandstone is seen to be made up of sharply angular grains of quartz, with an occasional fresh feldspar fragment and bits of carbonaceous material. The grains average about 0.05 mm. in diameter.

From a lithologic point of view the most striking feature of these rocks is their content of carbonaceous material, which, although slight and often absent, yet serves to contrast them with the overlying and underlying formations. In contrast to the succeeding reddish-brown feldspathic sandstone formation, the gray, fine-grained quartz sandstones and shales of the Momable suggest an origin under a permanent water-level at shallow depths in which flourished organisms whose presence is indicated by the carbonaceous content of the shales and by the possible fossil Aspidella.

Attention has been called by many observers to the resemblance between the gold-bearing series of Nova Scotia and Murray's Intermediate series of Newfoundland. It is to the beds comprising the Conception, Torbay, and Momable series lying below the Signal Hill series and above the Avondale volcanics that this lithologic resemblance applies. Judging from Fairbault's descriptions (Malcom, 1912, pp. 46–47) the Goldenville quartzites present certain resemblances to the Conception slate series, the banded argillite division of the western part of the field to the Torbay series, and the Halifax formation to the Momable series. Specimens of the Halifax slate collected by the writer from an outcrop in the yards of the Canadian Pacific terminal at Halifax are indeed indistinguishable, except for a more prevalent cleavage, from many characteristic specimens of the Momable series. Before any correlation may be suggested, however, it is necessary that a more intimate knowledge of the conformable or unconformable relations within the Newfoundland series shall be known, as well as more definite information concerning the relations of the gold-bearing series of Nova Scotia to the Cambrian. The Momable beds are also similar to the Animikie sediments as described by Coleman in respect to their content of carbonaceous material.

SIGNAL HILL SERIES

As near as can be judged from the descriptions of Murray and Howley (1881) and from the experience of the writer the Signal Hill series outcrops mainly in the troughs of synclines or synclinoria over an area extending for a length of about 200 miles in a north-northeast-south-southwest direction and about 75 miles at right angles to this.

The series consists of a very thick succession of reddish-brown, occasionally green, feldspathic sandstones and conglomerates, with intercalated shale beds and about 1,300 feet of greenish-gray, thick-bedded feldspathic sandstones at the base, giving a thickness estimated at about 10,000 feet. Murray's estimate of 3,120 feet for this series referred only to the beds on the west side of St. John's harbor, which constitute but a part of the series.

Thon-gallen or intraformational conglomerate beds are abundant. The majority of the conglomerate beds may be appropriately described as gravel or pebble beds, with the pebbles varying in size from one-fourth of an inch to an inch in diameter, and prevailingly subangular to rounded.

Because of the predominating sandy character of such a thick series of sediments; the repetition and often considerable thicknesses of conglomerate beds; the presence of so much fresh plagioclase and orthoclase throughout the rocks; the prevailing subangular character of the component grains; the predominating red color due to interstitial hematitic mud, to films of hematite, and to oxidized grains of basalt, rhyolite, and magnetite; the constant recurrence of thon-gallen beds; frequent cross-bedding; lithologic alternations of sandstone, conglomerate, and shale; and the absence of any limestone, fossils, or carbonaceous materials, the writer has been led to conclude that these beds originated as dominantly fluviatile deposits of subaërial origin in a subarid climate. It is quite possible that the basal 1,300 feet of green-gray sandstones accumulated under a permanent water-level; but if so the water was apparently drawn off or excluded at the time of accumulation of the succeeding reddish-brown series.

In thin sections from specimens of deep, livid-brown sandstone from Signal Hill the rock is found to consist of angular to subangular

grains of quartz, fresh plagioclase, orthoclase, and rhyolite and granophyre, with rarely a fragment of basalt. Accessory minerals comprise grains of primary epidote and occasionally abundant grains of magnetite. A film of hematite coats each grain, and in some specimens the interstices are filled with secondary quartz, sericite, or occasionally with epidote. The sericite is a secondary product, the result of recrystallization during shearing. In one section a rounded grain of primary epidote is coated with a film of hematite and is surrounded on the outside of this by a growth of secondary epidote. The cement of the green sandstone seems to be of an epidotic nature, apparently arising through a recrystallization of an impure argillaceous material. A chemical analysis of the reddish-brown sandstone serves to confirm the highly feldspathic nature of this rock.

TABLE IV

CHEMICAL ANALYSIS OF FELDSPATHIC BROWN SANDSTONE FROM NEAR SIGNAL HILL, ST. JOHN'S

SiO_2	71.38	Na_2O	2.28
Al_2O_3	14.25	K_2O	1.99
Fe_2O_3	4.75	H_2O+	1.20
FeO	.46	H_2O-	.21
MgO	.46		
CaO	3.01	Total	99.99

That the red color of the brown sandstones is due to hematite and to the oxidation of its iron content is evident from a comparison of the ferrous and ferric contents of the red and green sandstones. Although both have similar total contents of iron, 4.74 and 5.11 per cent respectively, expressed in terms of ferrous iron, the brown sandstone shows 4.75 per cent of ferric oxide and only 0.46 per cent of ferrous oxide, whereas the green sandstone shows 2.54 per cent of ferric oxide and 2.82 per cent of ferrous oxide.

The red color of the sandstones depends in varying degrees upon the primary deposition of a hematitic mud in the interstices of the sand grains; upon the deposition of hematite as a cement around the sand grains; upon hematite existing in the grains themselves as in the cleavage cracks of feldspar, or in oxidized basalt and rhyolite; and upon the hematite resulting from the oxidation of magnetite grains *in situ*.

The pebbles of the conglomerates in the vicinity of Signal Hill consist roughly of about three-quarters rhyolite-porphyry and the remainder granophyre, intraformational red shale flakes, and quartz, with occasional pebbles of basalt. The rocks of which these pebbles are formed are very similar to the rocks comprised within the Avondale volcanic series, and it is quite possible that they have been derived from that formation.[1]

In their stratigraphic relations, lithology, and mode of origin the Signal Hill series resemble the Jotnian of Sweden, the Torridonian of Scotland, and the Keweenawan of the "Canadian Shield." In the absence of vulcanism, so far as yet observed, they stand in contrast to the Keweenawan and Jotnian, but resemble the Torridonian. This is of special interest, since it has been shown by Hayes and van Ingen that this district during the succeeding Cambro-Ordovician period had a history which coincided even in minor detail with that of Wales.

INTRUSIVE ROCKS

The later pre-Cambrian rocks, more especially the early later pre-Cambrian beds, are intruded by several batholiths and stocks of igneous rock and are very intensively cut by dikes. In general, it may be said that the salic rocks have been intruded as molten masses of batholithic or stock type, with few apophyses or dikes, whereas the older basaltic or gabbroic magmas, to a preponderating extent, have been intruded as dikes.

The rocks, with the exception of the quartz syenite and granodiorite, whose position is unknown, are given in the order of their intrusion, beginning with the oldest. Those around Conception Bay comprise hornblende granite gneiss, hornblende gabbro and plagioclase gabbro without olivine but locally quartz-bearing, basic granodiorite, biotite granite and granophyre, quartz syenite, aplite and granophyre dikes intruding the granite, and younger dikes of rhyolite porphyry and diabase intruding all the older rocks. Near

[1] Murray describes the pebbles of the conglomerate at Signal Hill as composed "chiefly of white quartz, but with occasional pebbles of brown or red jasper, syenite or gneiss and slate." The writer examined 150 pebbles with the entirely different result given above.

Clarenville on Trinity Bay a mass of gabbro is intruded by granite, and both in turn are cut by younger dikes of aplite, rhyolite, and porphyrite dikes.

The hornblende granite gneiss shows a cataclastic texture and is believed to be the oldest rock in the district. Its outcrop was noted in only three areas of very small extent along the border of the Holyrood granite batholith.

The gabbros occur as small, irregular patches on the borders of and within the area of the Holyrood granite batholith, and also as huge dikes in the Conception slate series. They are predominantly of a blackish or dark speckled gray color weathering to an ashen gray. In grain they vary from fine to medium, and pegmatitic facies are entirely lacking. Mineralogically there seem to be two types, which can be distinguished by microscopic methods alone: one characterized by hornblende without augite; the other an augite gabbro in which the pyroxene may be unaltered or partially altered to hornblende or uralite.

Microscopically the augite gabbros are found to be predominantly hypautomorphic-granular in texture, occasionally becoming ophitic. The augite and plagioclase may be fresh, or partially or completely altered; and the alteration of these minerals seems to have proceeded independently, for fresh augite may be associated with altered plagioclase, and vice versa. The plagioclase may be partially altered to sericite, or flecked with sericite and partially replaced by quartz or epidote. The augite may be partially or completely altered to compact green hornblende or to an aggregate of uralite fibers or of uralite, quartz, and chlorite. The ilmenite is usually altered to leucoxene and is very small in amount. Pyrite is rare and magnetite relatively abundant. The peak of Holyrood Butterpot is formed of an elliptical mass of gabbro about 1,200 feet by 500 feet, completely surrounded by granite. It is peculiar in having quartz in small amount filling the interstices between the feldspars in such a manner as to indicate its origin as an original constituent, the last product of crystallization. Some of the augites are twinned, and others show idiomorphic basal sections. A chemical analysis of this rock is given on page 476, No. 2.

About six miles south of Manuels, lying between a series of green slates and the Holyrood granite, a more or less elliptical-shaped mass of gabbro forms a conspicuous ridge in the topography. This gabbro has a tendency toward a gneissic structure but without any particular evidences of dynamic metamorphism. It is quite intimately penetrated by ramifying apophyses of granite and by epidote veins, which are especially common along the joint planes. In thin section the rock is seen to be hypautomorphic granular to ophitic in texture and to consist essentially of light-green hornblende and labradorite. The feldspars are extensively altered to sericite, and some of the hornblende to intergrown fibers and blades of epidote, zoisite, and quartz. Many of the hornblendes are twinned parallel to the orthopinacoid, and by an occasional resemblance of crystal form give indications of an apparently primary origin. Whether this rock is the result of recrystallization during the intrusion of the granite or whether it is primary is difficult to say. A chemical analysis is given on page 476, No. 1. In this connection it may be well to note that where the road crosses Seal Cove Brook there is an outcrop of hornblende porphyrite with phenocrysts of hornblende up to 10 mm. in length and plagioclases averaging 2–3 mm. in length. In thin section this rock is found to consist of idiomorphic phenocrysts of labradorite and hornblende in a groundmass in some places consisting of a microcrystalline, elsewhere of an almost crypto-crystalline, aggregate of plagioclase microlites, quartz, and an altered ferromagnesian mineral in sparse amount. The plagioclases show a zonary banding.

To the west and south of Woodfords is a stock of granodiorite about two miles long and one-half mile wide, intrusive into the beds of the Avondale volcanic series. Dikes from this mass are exceptionally rare, but enough evidence was found to prove its intrusive nature. The rock is light colored and medium grained, consisting of pink orthoclase, black hornblende, and quartz. The latter is abundant in small grains which show upon a fresh surface only when closely examined. On the weathered surface, however, they stand out in relief and give to the rock the appearance of a typical granite. With the microscope the rock is found to consist of andesine, orthoclase, augite, and quartz, with abundant rods and grains of apatite.

The colorless augite is almost completely altered to pleochroic green hornblende and chlorite. A chemical analysis of this rock is given on page 476, No. 3.

Outcrops of a quartz syenite are found along the shore to the north of Chapel Cove. This rock has a very limited distribution, occurring in fault blocks brought into their present position by thrusting, and in places the rock is much crushed by the stresses to which it has been subjected. In the hand specimen the rock appears to be a white, medium-grained syenite, consisting of an aggregate of feldspars averaging 5 mm. in length. In thin section the rock is seen to consist of an aggregate of plagioclase feldspars, predominantly albite and to a minor extent oligoclase, with a groundmass of quartz and orthoclase in micrographic intergrowth filling the interstices. The rock is crushed and exhibits cataclastic texture in a high degree. A chemical analysis of this rock will be found on page 476, No. 4.

The backbone of the St. John's Peninsula is mapped by Howley (1907) as Laurentian. This rock in its northern half was found by the writer to bear intrusive relations to the Avondale volcanics and to constitute a granite batholith five to six miles in width and about forty miles in length, if its boundary to the south continues to coincide with that of Howley's Laurentian area. The eastern boundary, where it was followed by the writer for several miles, is delimited by a fault plane. Along the west side the beds are very much disturbed and folded. The rock is a pink, medium-grained, equigranular, biotite granite, consisting essentially of quartz, orthoclase, albite, oligoclase, and chlorite, the latter believed to be derived from biotite. Fresh flakes of original biotite, however, are found only in occasional sections. A chemical analysis of the rock appears on page 476, No. 5.

One of the most striking and interesting features of the geology along Smith and Random sounds at the head of Trinity Bay is the way in which the early green slates of that region have been rent, riven, and intruded by a great series of approximately parallel dikes of porphyrite and basalt. At one locality there were counted 32 dikes in a distance of about 350 yards. As a rule, however, the dikes are not as frequent as this; yet they are never absent for any

great distance. Their general strike is approximately north-south. About half the dikes are between two and five feet in width, and the rest are about equally divided between dikes ten to fifteen feet and those thirty or more feet in width. In addition to the dikes in the slate series several dikes and sills were found intruding the Cambro-Ordovician rocks, and dikes in the Signal Hill and Random formations are present but rare. The porphyrite dikes are variable in their mineralogical composition and comprise hornblende porphyrites, labradorite porphyrites, and augite porphyrites or basalts.

TABLE V

CHEMICAL ANALYSES OF INSTRUCTIVE IGNEOUS ROCKS AROUND CONCEPTION BAY

	1	2	3	4	5
SiO_2	48.54	51.34	59.18	69.52	71.82
Al_2O_3	20.62	18.94	18.21	16.85	16.07
Fe_2O_3	5.39	3.29	2.73	.03	1.22
FeO	5.53	6.49	3.62	1.65	1.60
MgO	4.77	4.55	2.51	.18	.40
CaO	8.16	8.84	4.23	1.37	1.66
Na_2O	3.14	2.19	3.84	5.09	3.27
K_2O	1.23	1.09	3.26	3.73	3.07
H_2O+	1.85	2.12	1.85	.89	.71
H_2O-	.17	.11	.20	.05	.19
TiO_2	.20	.34	Undet.	.21	Undet.
MnO	.19	.29	.16	.09	.13
Total	99.77	99.59	99.79	99.66	100.14

1. Hornblende gabbro from about 6 miles south of Manuels.
2. Quartz bearing gabbro from Holyrood Butterpot.
3. Granodiorite from near Woodfords.
4. Quartz syenite from Chapel Cove.
5. Biotite granite from interior of St. John's Peninsula.

The former are found in the pre-Cambrian slates, but only the last named in the Cambro-Ordovician beds.

In the region about Conception Bay the granite of the Holyrood batholith, the gabbro, quartz syenite, and dikes of rhyolite porphyry and diabase are all overlain unconformably by Lower Cambrian sediments. Salic dikes were not found intruding beds younger than the Conception slate series, and femic dikes are far less frequent in formations above this series than in those below it and constituting it. Whether this is due to the different character of the formations, to their different stratigraphic position, or to their different age,

is an open question. What little evidence there is seems to point toward a period of batholithic and dike intrusion at a time succeeding the period of deposition of the Conception series and preceding that of the Signal Hill series. No dikes whatever were found intruding the Cambro-Ordovician beds in the region of Conception Bay, but in the vicinity of Trinity Bay infrequent dikes of a distinctive character do intrude these beds and undoubtedly belong to a younger period of intrusion, possibly that of the Taconic revolution, or related to the period of vulcanicity represented by vast flows of lava in the Notre Dame Bay region about fifty miles to the northeast. This period of intrusion during the pre-Cambrian corresponds to a similar period of intrusion of granite into the volcanic series of the Blue Ridge of Maryland and Virginia described by Keith (1892), or the Proterozoic batholiths of the Lake Superior region described by Allen (1915, p. 717) which he suggests are post–Middle Huronian or pre–Upper Huronian.

Geographically, chemically, and physically the volcanics, plutonics, and dikes of the Conception Bay region appear to be genetically allied. Thus the gabbros, quartz-bearing gabbro, hornblende porphyrite with quartzose groundmass, granodiorite, quartz syenite, biotite granite, granophyre, and aplite form a series of rocks with an ascending silica ratio, belonging to the same geographical area and very probably to the same period of intrusion. Again, the analyses of the Holyrood granite, rhyolite porphyry near Holyrood, and a rhyolite flow from the Avondale volcanics near Manuels, constituting a batholith, a volcanic neck, and a volcanic flow respectively, show but slight variation in composition, although the texture varies widely. The chemical differences between the granite on the one hand, and the rhyolite porphyry and rhyolite on the other, are the usual relative increase in silica and loss of alumina, lime, magnesia, and iron in the volcanic facies. Again, the plutonic gabbros, a volcanic plug of plagioclase basalt near Manuels, and the Blue Hills basalt flows may be cited as textural facies of a similar basic magma. The repeated recurrence and abundance of intrusions of magma of basaltic composition in dikelike form throughout the entire peninsula, in contrast to the restricted local character of the salic intrusions with their associated infrequent dikes, rather

impress one with the idea that a basaltic magma was the one from which the salic differentiates originated.

CONCLUSION

The points brought out in this paper which it is desired to emphasize are as follows:

1. The confirmation of the local glaciation of the Avalon Peninsula, of the control of faults and fractures over the lineaments of the topography, and of the fiord nature of the coast.

2. The description and confirmation of the presence of a thick series of volcanics at the base of the pre-Cambrian section.

3. The presentation of evidence pointing toward the origin of the members of the later pre-Cambrian series, as follows:

a) The Avondale volcanics as subaërial accumulations of volcanic materials derived from volcanoes of the central type.

b) The Conception slate series as materials derived from rocks resembling the Avondale volcanics swept into the sea in a comparatively fresh, unaltered condition.

c) The Momable formation as well-decomposed marine sediments with traces of organic life.

d) The Signal Hill reddish-brown sandstone series as dominantly subaërial fluviatile deposits in a subarid climate, derived from a re-working of volcanic rocks resembling members of the Avondale volcanics.

4. The evidence of a comagmatic series of igneous rocks intruded probably at some time during early or middle Proterozoic time.

5. The entire series from bottom to top is derived directly or indirectly from rocks of volcanic origin.

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CURIOUS EROSION FEATURE IN WEST TENNESSEE CLAYS

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Recently the writer had occasion to observe a rather odd and striking phenomenon. The clay strata of West Tennessee lie in nearly horizontal beds of unconsolidated sands of the Ripley and Lagrange (Wilcox) formations and are very liable to active erosion. During torrential rains, which are common in this region,

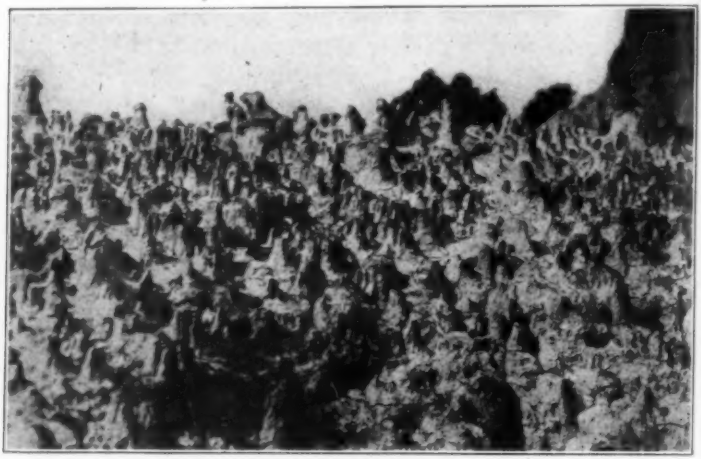

FIG. 1.—Miniature erosion pillars in clay. (Scale, 1 inch = 1 foot.)

small columns are sometimes carved in the surface of the exposed clay. These have been termed "miniature hoodoos" by the writer, for they are in fact small editions of the pillars or "hoodoos" so well known in Monument Park, Colorado, and have the same origin. They are rarely more than six inches high, are circular or elliptical in horizontal section, and generally closely

spaced (15–20 per square foot). Thin fragments of hardpan (ferruginous sandstone) commonly form the protective capping and are derived from the overburden. Other substances, such as leaves, bits of wood, and concretions, function in the same way. In short, any small, flat piece of coherent matter will do. These miniature hoodoos are very abundant in this region and are especially characteristic of very plastic clays.

Reviews

The Principles of Economic Geology. By W. H. Emmons. New York: McGraw-Hill Book Co., Inc. Pp. 606, with 208 figures. 1918.

In *The Principles of Economic Geology* Professor Emmons has aimed to give advanced students of geology a general survey of the science of mineral deposits. The fuels have purposely been omitted, however, as to have treated them adequately would have enlarged the book unduly, and evidently for the same reason the non-metalliferous deposits are somewhat briefly described, receiving but one chapter of the twenty-eight in the book. The volume is thus in essence a condensed treatise on ore deposits; its central concept is that most ore deposits (except an important group of sedimentary origin) are genetically related to igneous rocks.

The first chapter consists almost wholly of definitions, such as ore, protore, etc., a necessary groundwork, but it forms a rather heavy introduction to the subject and is likely to dull the interest of students coming fresh to the subject; fortunately the chapter is but three pages long. A suggestive outline of the objects of economic geology, its problems, and its broader relations to petrology and geology would perhaps make a more attractive introduction. The second chapter takes us deep into the subject, namely, the classification of ore deposits. Primary ore deposits are grouped under eight major heads:

1. Deposits formed by magmatic segregation; consolidated from molten magmas.

2. Pegmatite veins; deposited by aqueo-igneous magmatic solutions.

3. Contact-metamorphic deposits; deposited in intruded rocks by fluids passing from consolidating intruding rocks.

4. Deposits of the deep vein zone; formed at high temperature and under great pressure, generally in and along fissures.

5. Deposits formed at moderate depths by ascending hot solutions.

6. Deposits formed at shallow depths by ascending hot solutions.

7. Deposits formed at moderate and shallow depths by cold meteoric solutions.

8. Sedimentary deposits; chemical, mechanical, organic, etc.

These classes are then briefly characterized, perhaps somewhat too briefly to differentiate them clearly in the student's mind at this stage of his knowledge of the subject. For example, the characterization of contact-metamorphic deposits is insufficient to distinguish them sharply from deposits of classes 4, 5, and 6.

The next eight chapters take up one by one the several classes of the scheme. They are models of clear and concise presentation.

In the chapter on the sedimentary deposits is given an interesting diagram that shows approximately what proportion of the primary ores and protores of each of the various metals occur in the eight groups of the genetic classification.

Chapters 11 to 21 inclusive deal with the more general phases of the subject, such as primary ore shoots, the origin of thermal metalliferous waters, and so on. The chapter on Superficial Alteration and Enrichment is of course particularly good, as is to be expected of a field that the author has so notably made his own. It is somewhat surprising, however, to find that he has made no use of the newer solubility determinations of the metallic sulphides as given in Stieglitz' *Qualitative Analysis* or in Abegg's *Handbuch der Anorganische Chemie;* had he used these, rather than those of Weigel, he would have found less difficulty in reconciling them with the known facts of secondary enrichment.

The second half of the book (chapters 22 to 28, comprising 299 pages) treats of the metals and more important non-metals. The chief valuable minerals of each metal and non-metal are described, chiefly in their economic aspects, the genesis of the deposits is sketched, the age of the deposits occurring in the United States is discussed, and certain specific or distinctive features of the geology of each substance, such as sulphide enrichment in the chapter on copper, are specially considered. Although some economic geologists have objected to this mode of treatment by substances, it is an eminently satisfactory way of giving the subject concreteness to the student. As DeLaunay says, the treatment by types of deposits, in spite of important advantages, has the grave fault of scattering the descriptions of deposits of the same substance according to a system that is necessarily somewhat hypothetical and arbitrary. The general treatment of each metal or non-metal is followed by descriptions of mining districts, practically all of which are chosen from the United States. For some reason not clearly apparent the order in which they are described conforms neither with the genetic classification of the first half of the book nor with the order of their

commercial importance. In the chapter on iron, the Lake Superior deposits receive an undue amount of attention in view of the title of the book, and following what seems to have become a convention among those intrusted to teach geology, a large number of stratigraphic columns built up of many formations and members, doubtless of interest to local geologists, have been introduced, but they add little in elucidating the principles of the science. The reviewer would like to see the chapter on iron recast in accordance with the genetic classification adopted in the book. As illustrating the first category of the classification, the descriptions of the districts might then begin with the igneous iron ores of Kiruna, Sweden, which have been carefully studied by many able geologists and concerning which there is, as a result of the attrition of ideas, a solid nucleus of established fact. It seems desirable that this mode of treatment be extended to the other metals also, and that the representative districts be selected regardless of whether they are or are not in North America. Although the author has purposely chosen the illustrative districts almost wholly from North America, the procedure can hardly be commended, as it encourages provincialism and seems rather a concession to our American linguistic laziness. In the chapter on copper seven of the eighteen districts described are those containing disseminated deposits, which adds much to the amount of information presented, but does not increase the number of principles exemplified. For some of the "porphyry coppers," descriptions of types not now illustrated by the book might profitably be substituted, such as those of Mansfeld, Sulitelma, and Little Namaqualand.

In naming this volume *The Principles of Economic Geology*, Professor Emmons has given it a highly attractive title—one which arouses the expectation that the book thus distinguished will deal in a broad and stimulating way with the firmly established generalizations of the subject. If in places it deviates from the ideal suggested by its title and becomes burdened with details, these departures are after all easily forgotten in view of the general excellence of the book. The subject is accurately, clearly, and succinctly presented, and is well illustrated by numerous carefully chosen text figures. The author has achieved the plan he set himself to accomplish—to give a conspectus of the subject for advanced students of geology—and for this purpose the book is undoubtedly the best text on economic geology that has yet been written.

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